

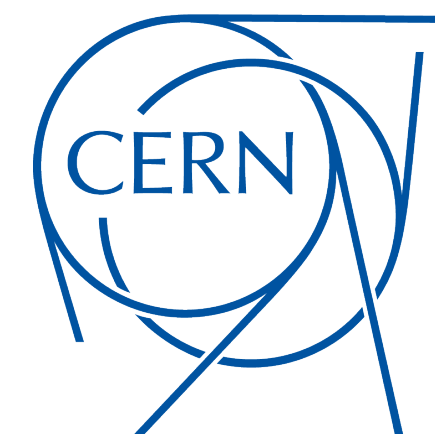
# ***“Jet Different”***

Summary of BOOST2021

BOOST  
Online 2021

<https://indico.cern.ch/e/BOOST2021>

M. LeBlanc (CERN)  
Snowmass Energy Frontier Workshop (EF05 Session)  
30 August - 3 September 2021



# BOOST 2021

- Took place from 2-5 August, totally online.
- Unusual format! All talks were pre-recorded. ‘Live’ conference time was almost completely dedicated to discussions.
  - Collected questions ahead of time, partially by asking self-identified early-career participants to review them!
- All discussion sessions were recorded, all material is professionally captioned and available for your viewing pleasure!
  - Because of this, I will not try to be exhaustive in this brief summary: I will instead try to provide a few of my own impressions / synthesis of ideas discussed at the meeting this year.
    - Leaving out ML (Nachman, yesterday @ EF05), ions (EF07 session after this one), many other things ...
- Pro tip: you can “BOOST your BOOST” by speeding up video playback speed on CDS!

<https://indico.cern.ch/e/BOOST2021>



The screenshot shows the BOOST 2021 Indico conference page. The header is blue with the text "BOOST 2021 : 13th International Workshop on Boosted Object Phenomenology, Reconstruction and Searches in HEP". Below the header, the dates "2-5 August 2021" and "Online" are listed, along with the "Europe/Paris timezone". A search bar is on the right. The left sidebar contains a menu with links: Overview, Community Values, Call for Abstracts, Timetable, Contribution List, My Conference, My Contributions, Collecting Discussion Items, Speaker instructions, Editing, Papers, Book of Abstracts, Registration, Participant List, Gather.Town, Fee Payment, and Contact. The main content area features the "BOOST Online 2021" logo, a description of the conference as the thirteenth in a series, and a list of topics: Phenomenology and searches using jet substructure, New jet substructure observables and algorithms, QCD measurements and modeling, Jet reconstruction performance, Pileup mitigation, Heavy-ion collisions, and Future colliders. It also lists previous editions from 2009 to 2014.

**BOOST 2021 : 13th International Workshop on Boosted Object Phenomenology, Reconstruction and Searches in HEP**

2-5 August 2021  
Online  
Europe/Paris timezone

Enter your search term

**BOOST Online 2021**

BOOST 2021 is the thirteenth conference of a series of successful joint theory/experiment workshops that bring together the world's leading experts from theory and LHC experiments to discuss the latest progress and develop new approaches on the reconstruction of and use of jet substructure in order to search for new physics and study the standard model.

**This year's conference will be exclusively online, with talks presented through Zoom and informal discussions on Gather.Town. Contributions will be pre-recorded by speakers for attendees to watch asynchronously. Each contribution will have 15' live for review and discussion during the conference. There will additionally be longer, live review talks to start the conference and a live panel discussion to close it.**

The conference will cover the following topics:

- Phenomenology and searches using jet substructure
- New jet substructure observables and algorithms
- QCD measurements and modeling
- Jet reconstruction performance
- Pileup mitigation
- Heavy-ion collisions
- Future colliders

Previous editions:

- [SLAC](#) (2009)
- [Oxford](#) (2010)
- [Princeton](#) (2011)
- [Valencia](#) (2012)
- [Flagstaff](#) (2013)
- [London](#) (2014)

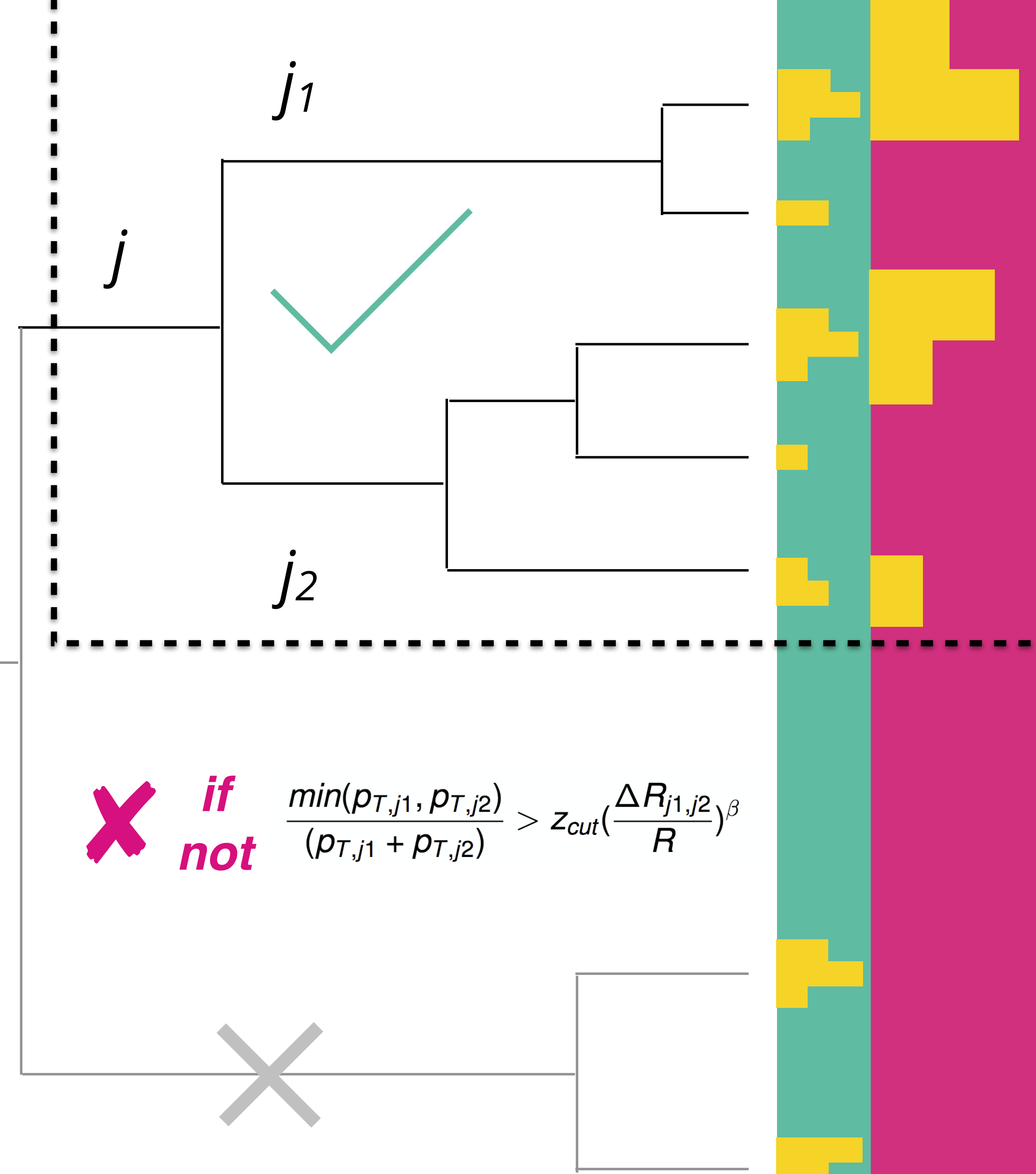
Contact  
✉ [boost2021-loc@cern.ch](mailto:boost2021-loc@cern.ch)

*A photo of our beautiful conference venue ...*

Soft-drop / mMDT  
is still centre-stage!

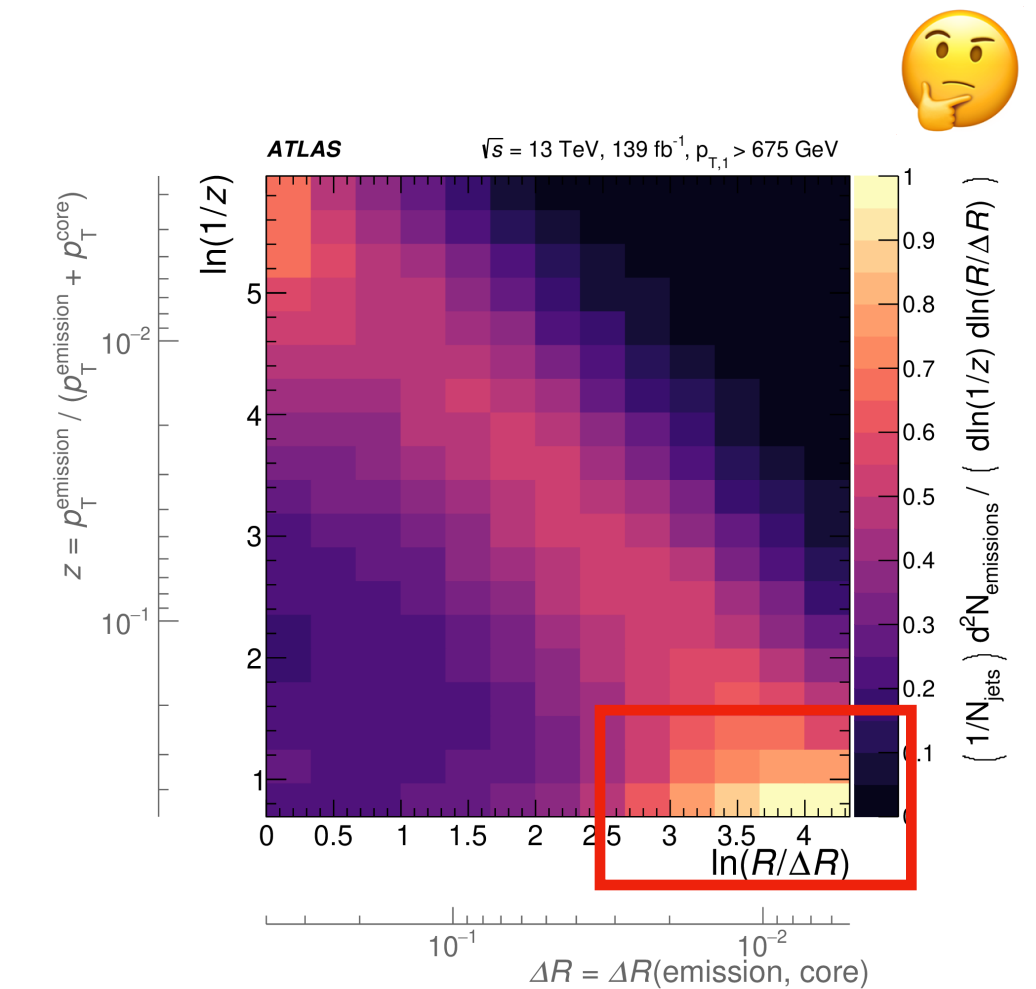
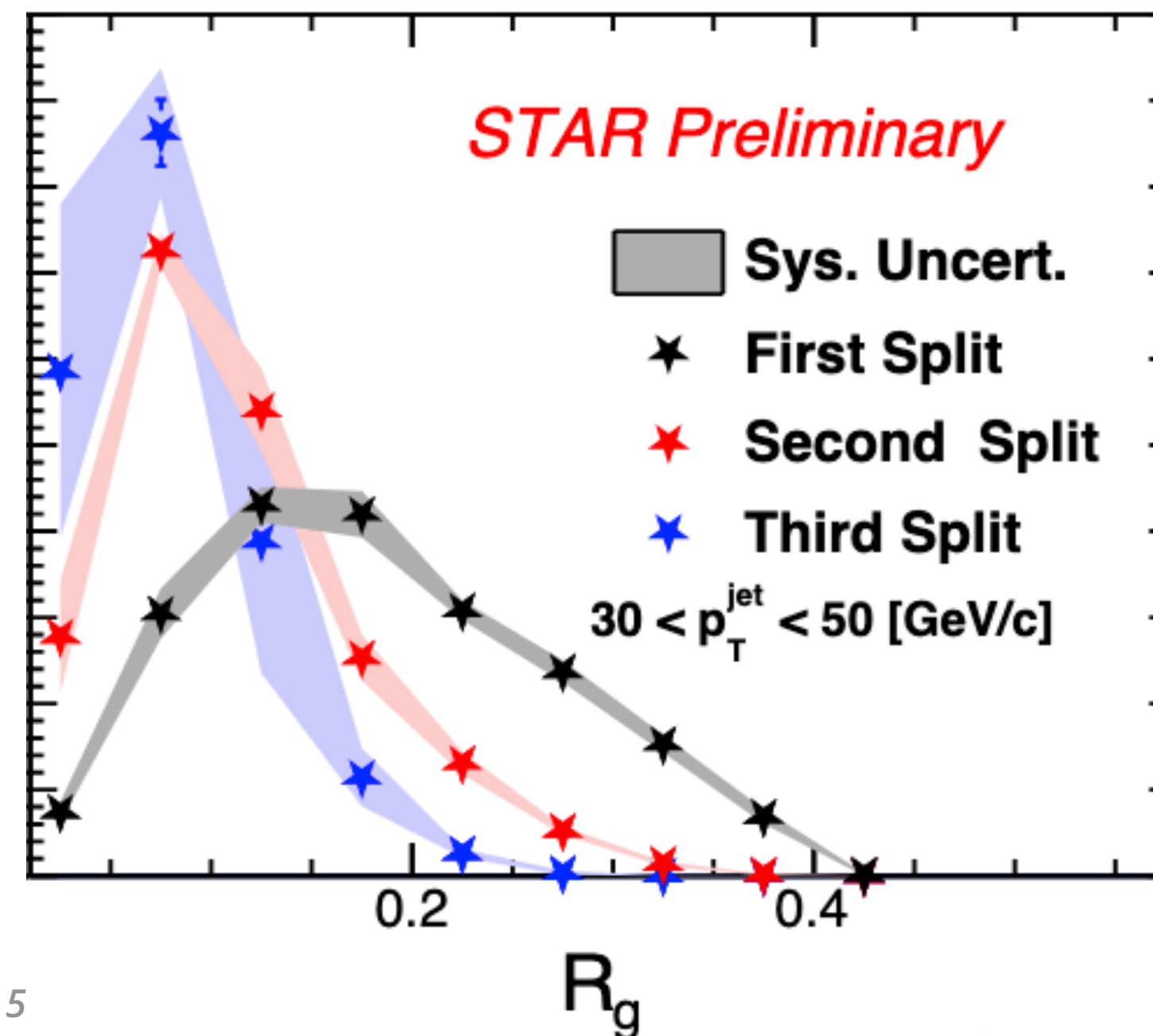
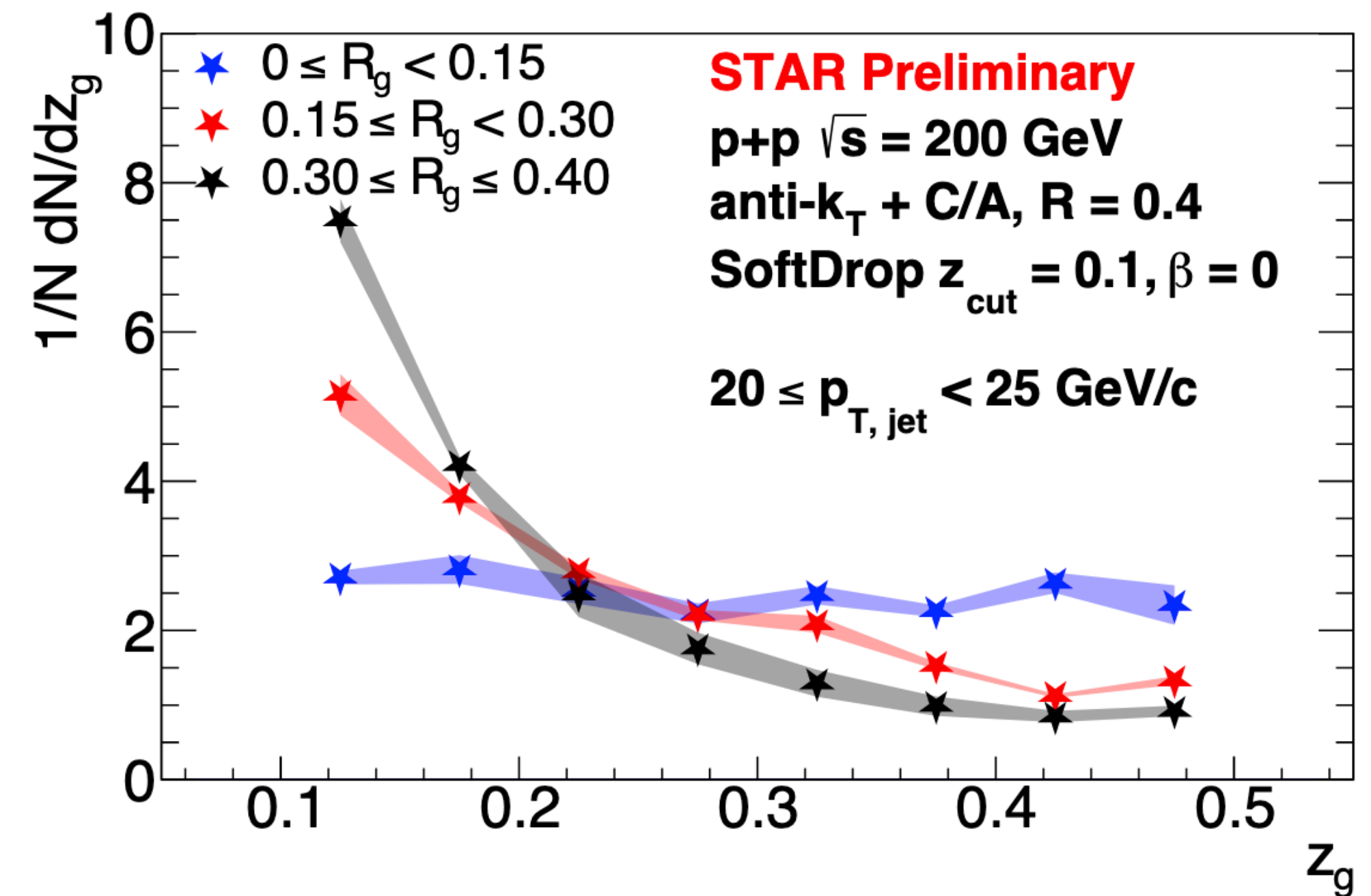
# Soft-drop / mMDT

- This algorithm has played a central role in understanding JSS since its proposal in 2013 / 2014.
  - Removes **Non-Global Logarithms**, first JSS predictions beyond LL accuracy all rely on the SD/mMDT procedure.
  - **Recluster** jet constituents with **C/A algorithm**, then **remove soft & wide-angle radiation** failing SD condition.
- Observables characterizing the hardest splitting in SD jets have been studied thoroughly, by experiment and theory:
  - $\rho = \log_{10}(m_j / p_{Tj})$
  - $z_g = p_{Tj2} / p_{Tj1}$
  - $R_g = \Delta R(j_1, j_2)$
- Many other schema for understanding JSS are built from this tree-based declustering technique (e.g. Lund jet plane).



# STAR starts to BOOST!

- Previous measurements of  $\rho$ ,  $z_g$ ,  $R_g$  by ATLAS, CMS and ALICE.
- New: measurements of SDOs in  $pp$  collisions by STAR, at BNL's RHIC facility.
  - Differential  $z_g$ ,  $R_g$  measurements highlight hard, collinear splittings within the core of jets.
- Not appearing in this summary: new generalized angularity measurements by CMS, and new measurements of  $b$ -jet fragmentation by ATLAS.



# zg at NLL'

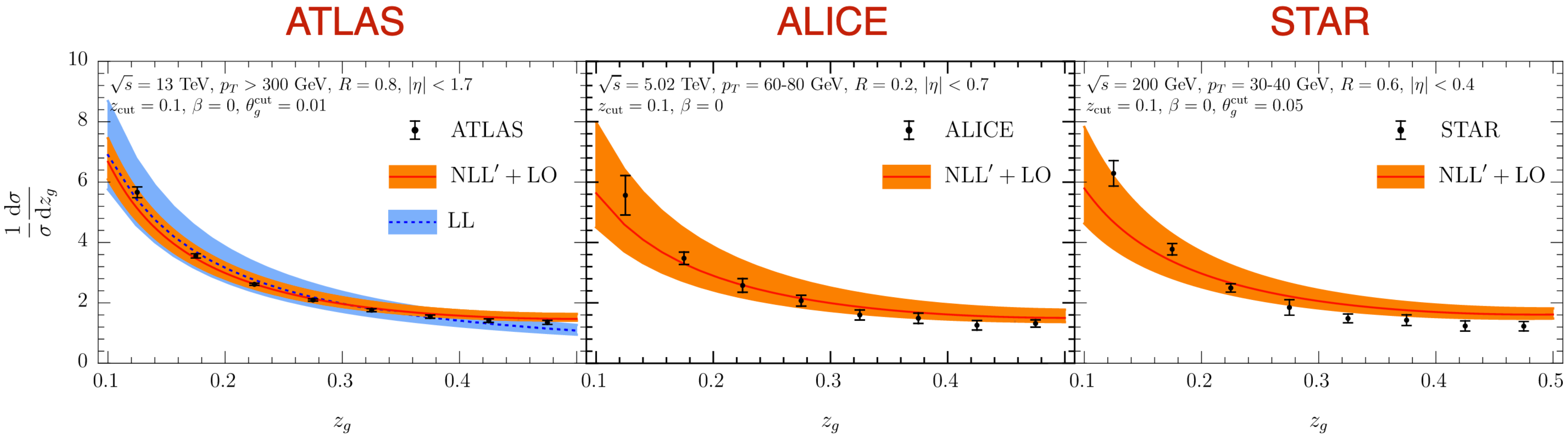
For  $\beta \geq 0$ ,  $z_g$  is IRC unsafe

$z_g = 0$

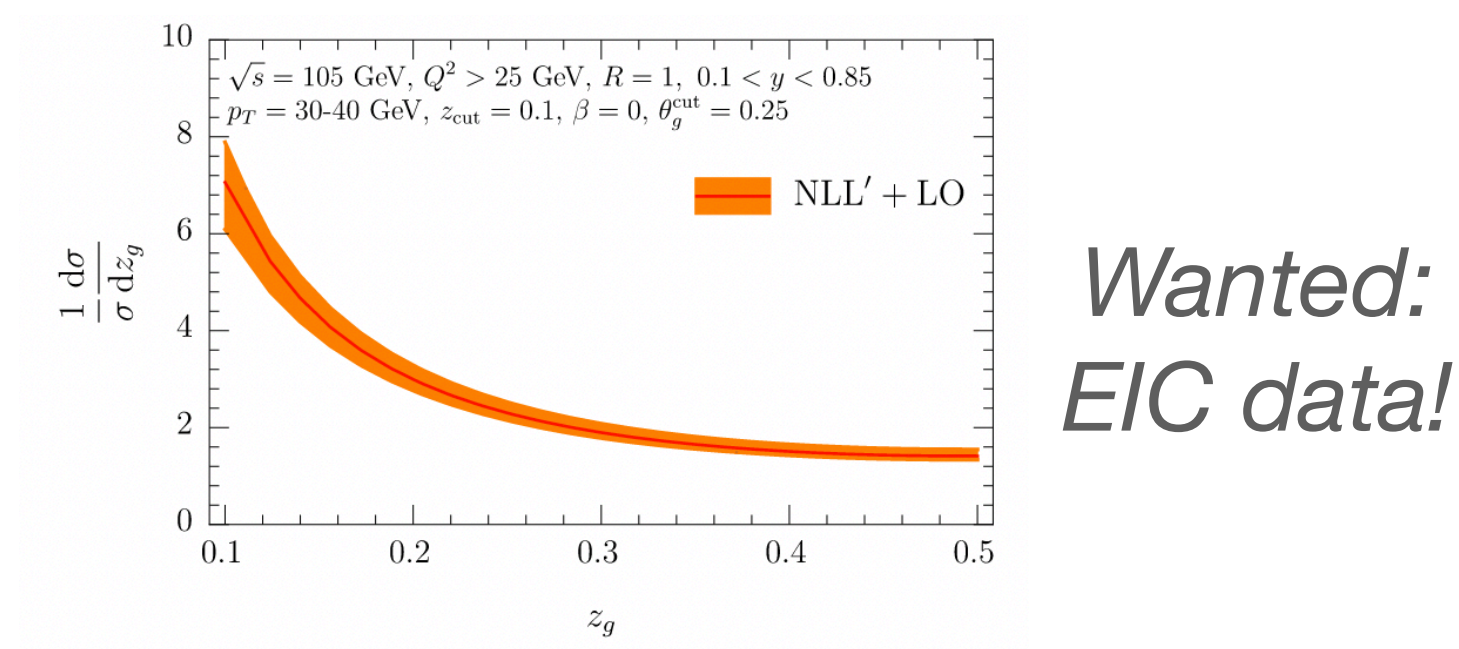
$z_g \neq 0$

$\times$

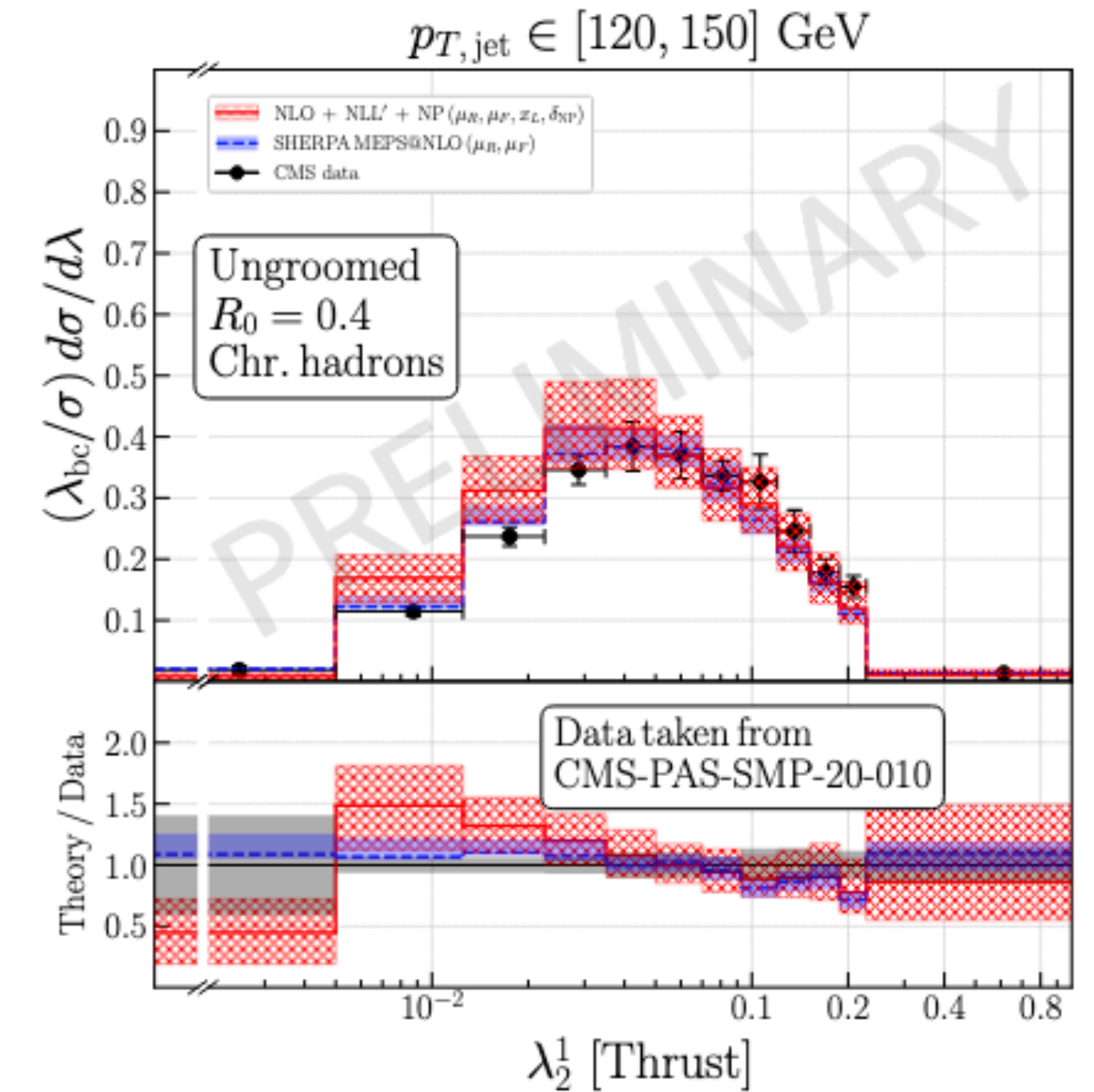
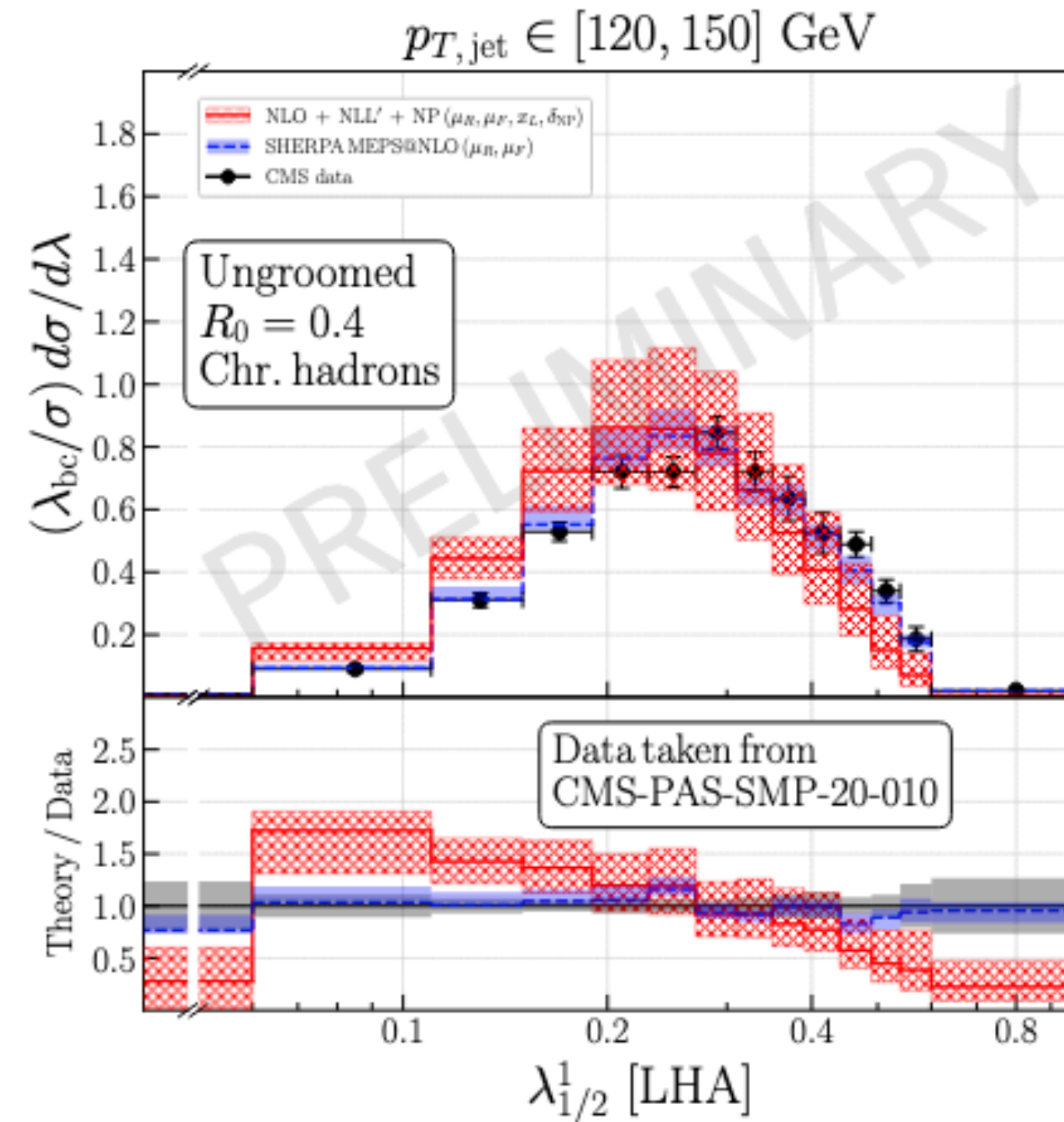
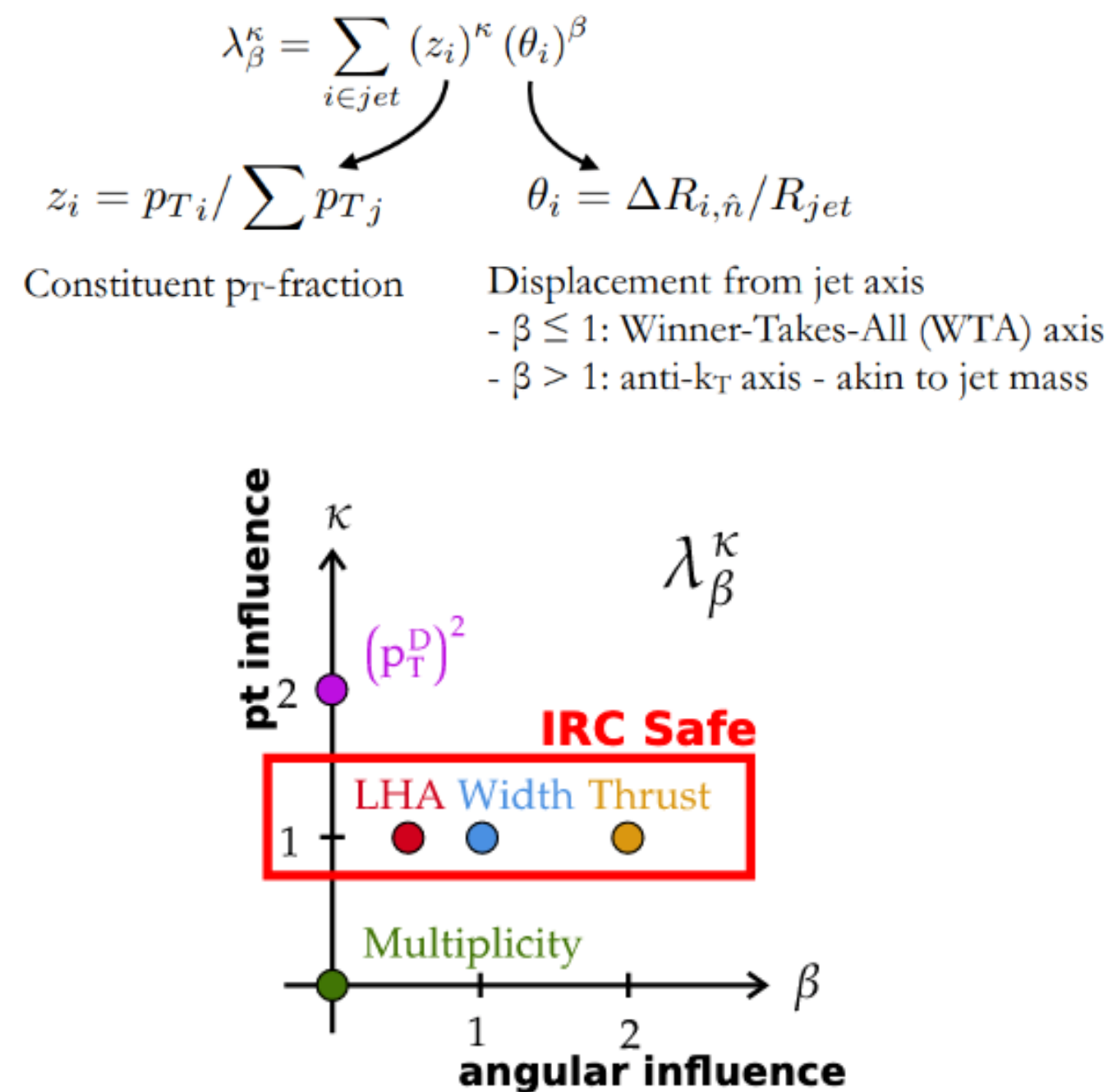
Larkoski, Marzani, Thaler '15



- New theory calculations predict soft-drop  $z_g$  at NLL by conditioning on  $R_g$ .
- Compared to available, complementary measurements from ATLAS, ALICE & STAR!
- Predictions already available for EIC — JSS techniques relevant at multiple facilities!



# Generalised angularities at NLO+NLL'+NP



- New measurement of generalized jet angularities in soft-drop jets from CMS, compared to brand-new predictions at NLO+NLL'+NP — good agreement observed!
- CMS measurement tries to probe differences between samples with different q/g composition: worth reading to find out the details.

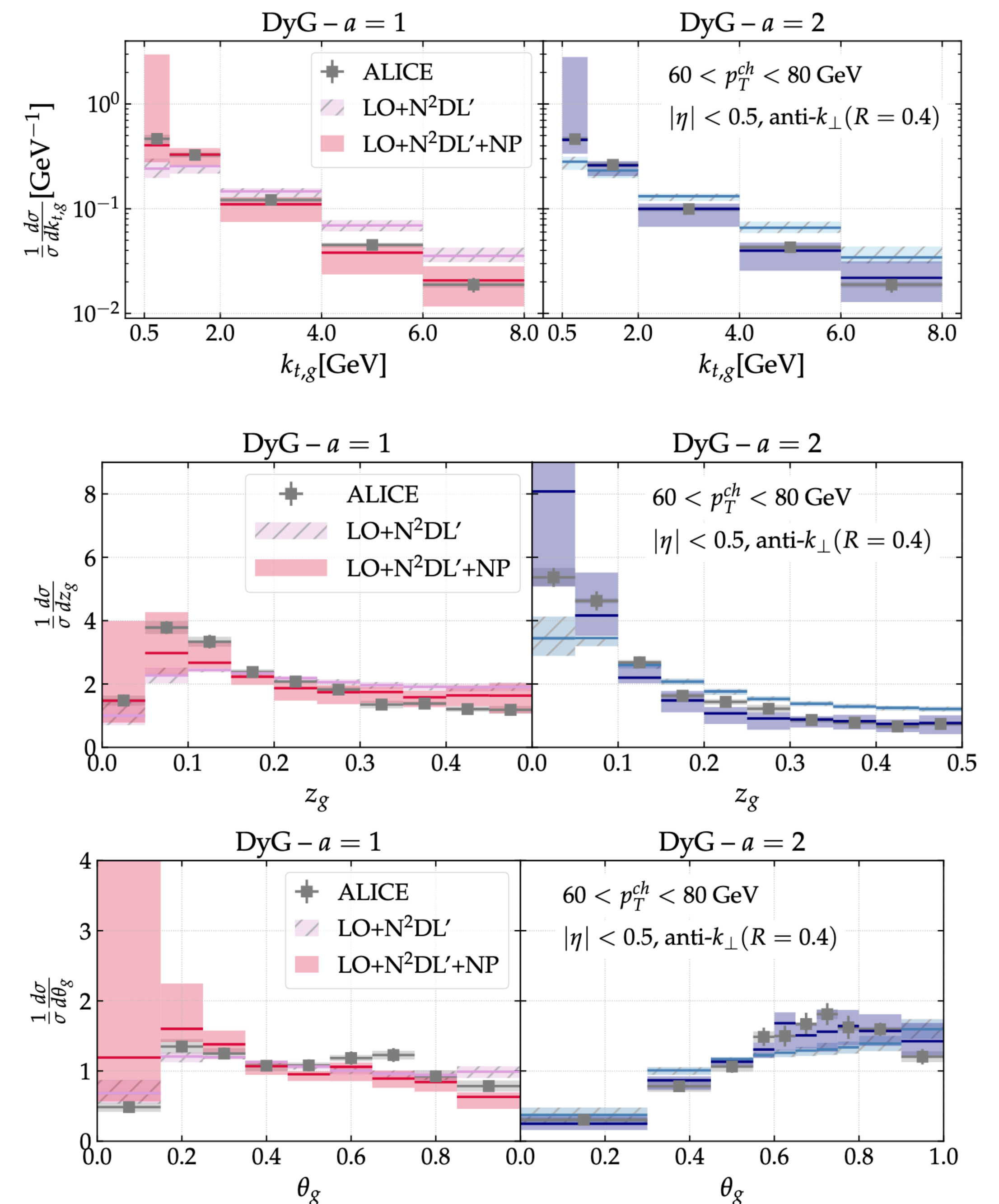
... but, we are starting to have  
more options!

# What comes after soft-drop? ... Dynamical grooming?

- Dynamical grooming (“DyG”) proceeds similarly to soft-drop, but instead bases grooming decision on the hardest splitting, found by maximizing

$$\kappa^{(a)} = \frac{1}{p_{t,\text{jet}}} z(1-z)p_t \theta^a$$

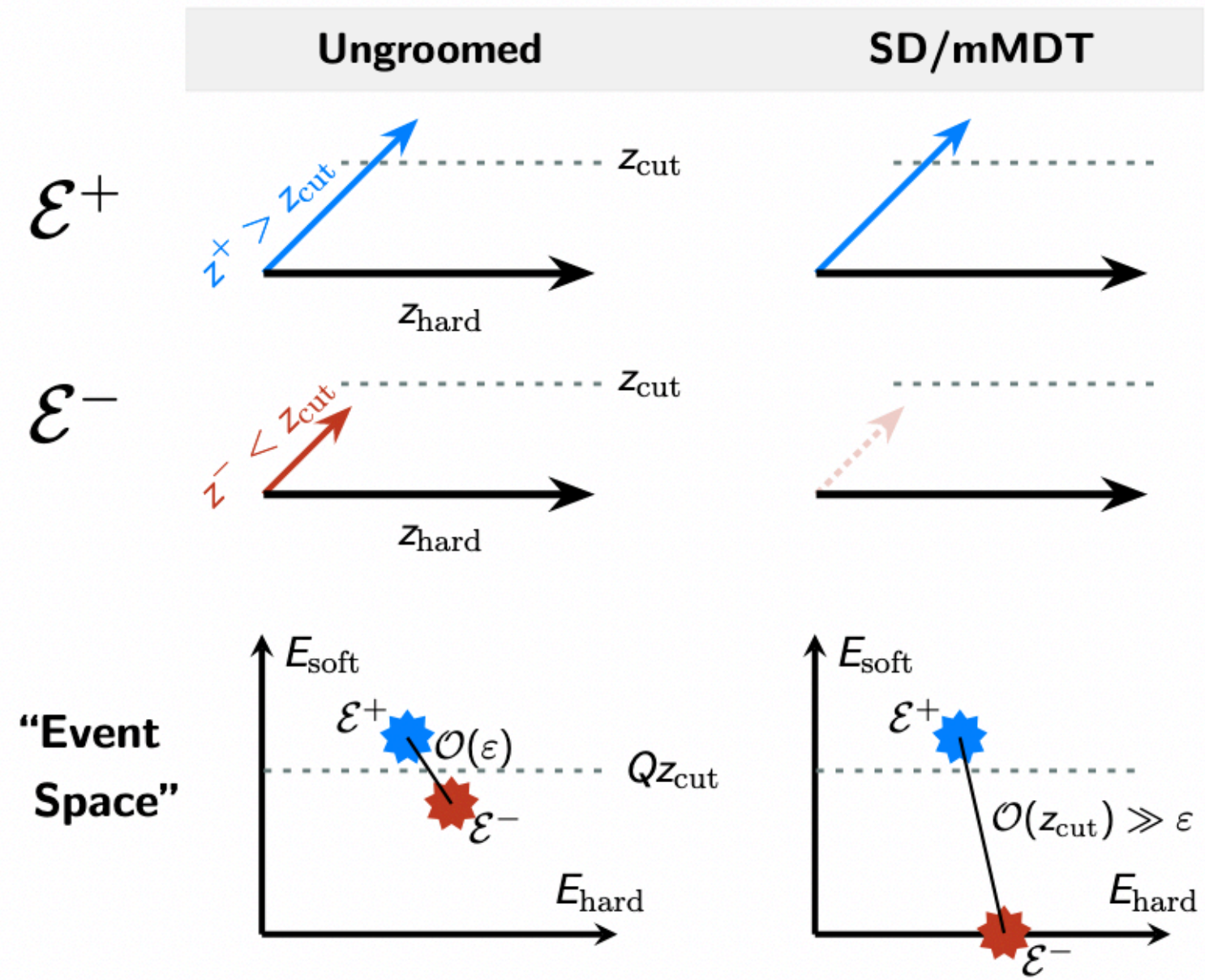
- Shown to be more resilient to hadronisation.
- Calculations at N<sup>2</sup>DL accuracy, no clustering logs.
- ALICE has measured  $\theta_g$ ,  $z_g$ , and  $k_{t,g}$ : good agreement with new predictions!



# What comes after soft-drop? ... Recursive Safe Subtraction?

- One undesirable ‘feature’ of the soft-drop algorithm is sensitivity to the hard cut-off  $z_{\text{cut}}$ :

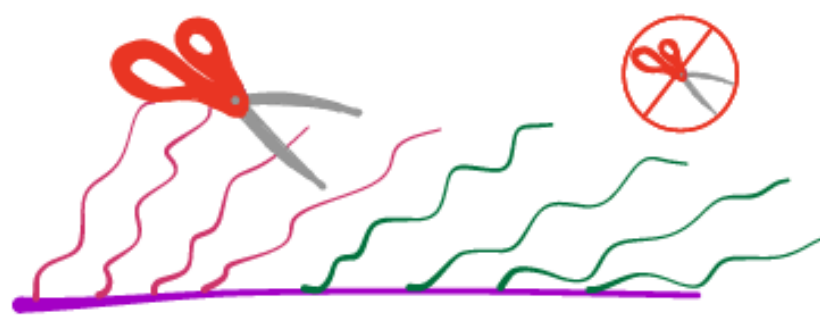
Before grooming,  
 $E^+$  and  $E^-$  are  
similar  
— but soft-drop  
makes  
them very different!



- Newly-proposed “continuous grooming” based on ideas from geometry, solves this pathology.

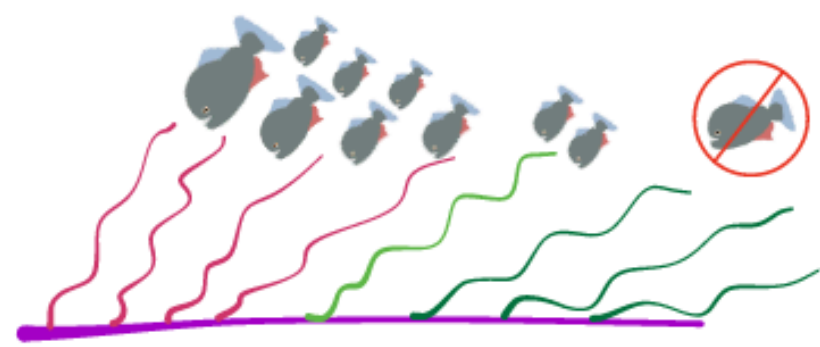
## Soft Drop/mMDT

- Check  $z > z_{\text{cut}}$ .
- Failed:** Groom softer branch and continue.
- Passed:** Keep remaining jet.

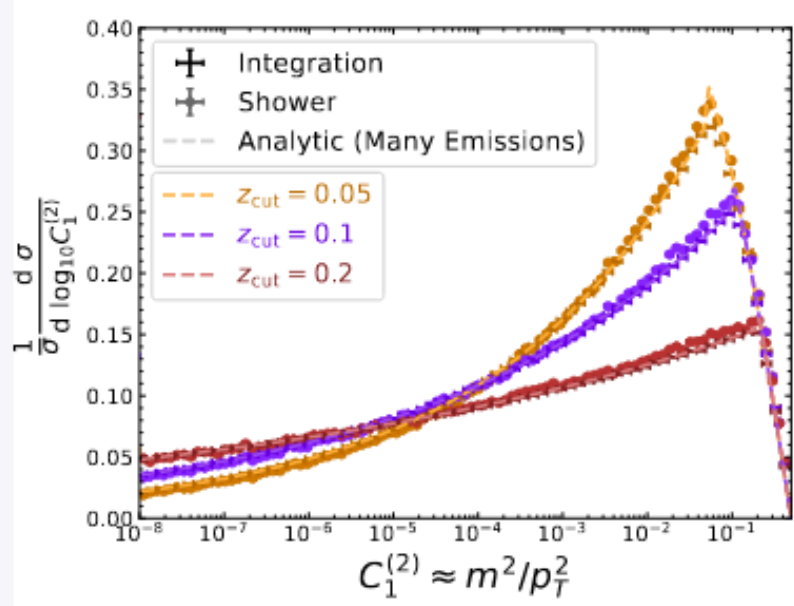


## PIRANHA-RSS ( $f = 1$ )

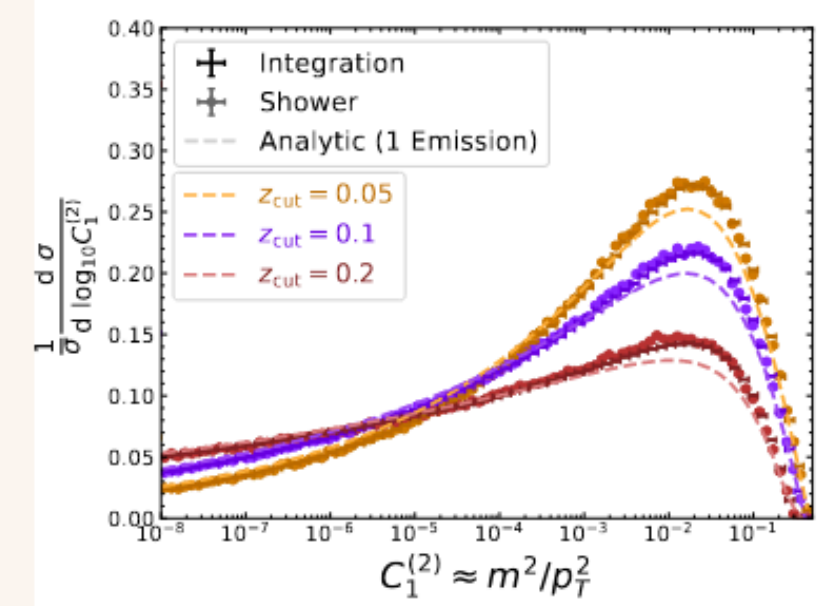
- Check  $z > z_{\text{cut}}^{(n)}$ .  
( $z_{\text{cut}}^{(0)} = z_{\text{cut}}$ )
- Failed:** Groom softer branch, set  $z_{\text{cut}}^{(n+1)} = z_{\text{cut}}^{(n)} - z$ , and continue.
- Passed:** Remove energy from the softer branch,  $z \rightarrow z - z_{\text{cut}}^{(n)}$ , and keep remaining jet.



## Soft Drop/mMDT

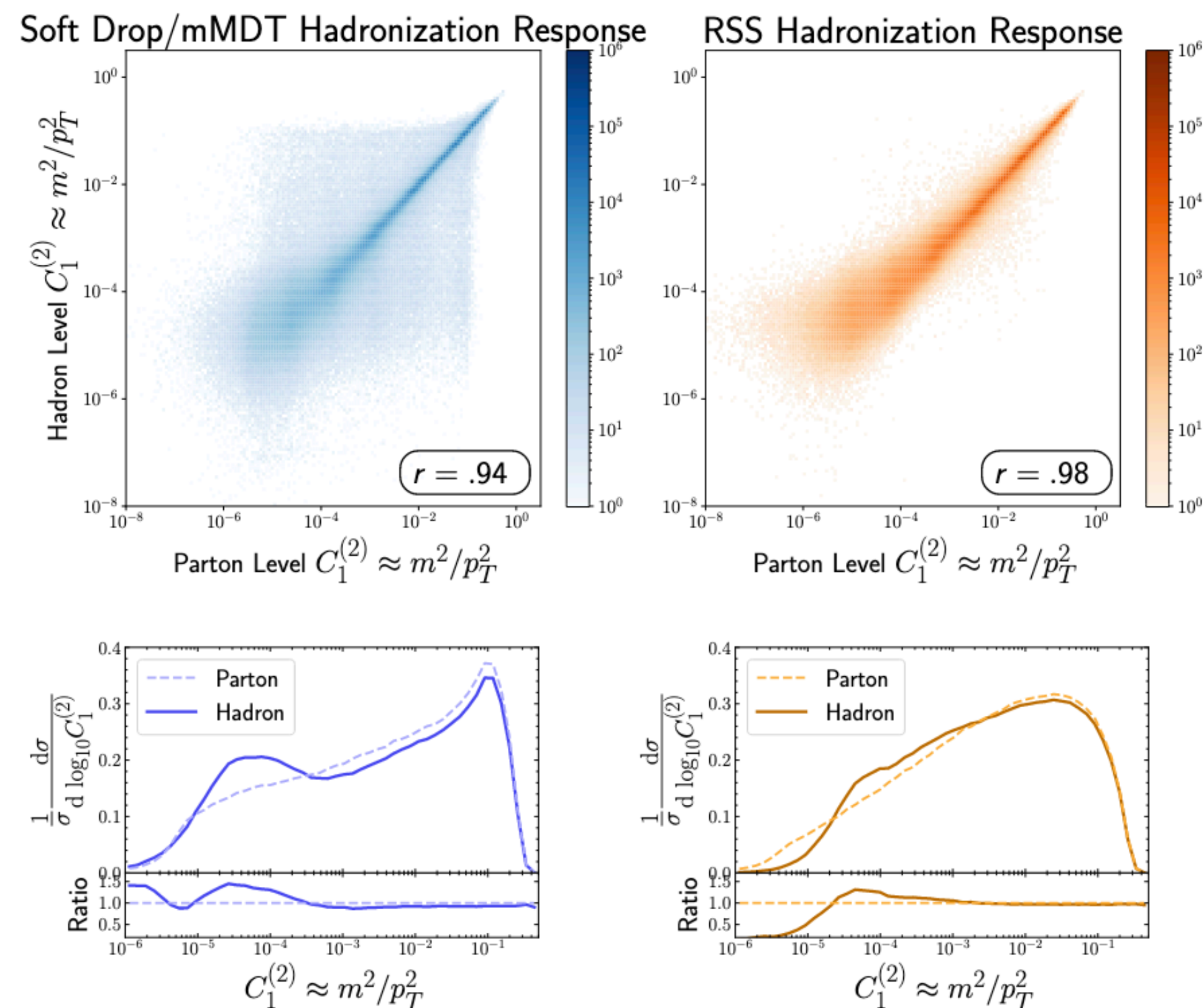


## PIRANHA-RSS ( $f = 1$ )



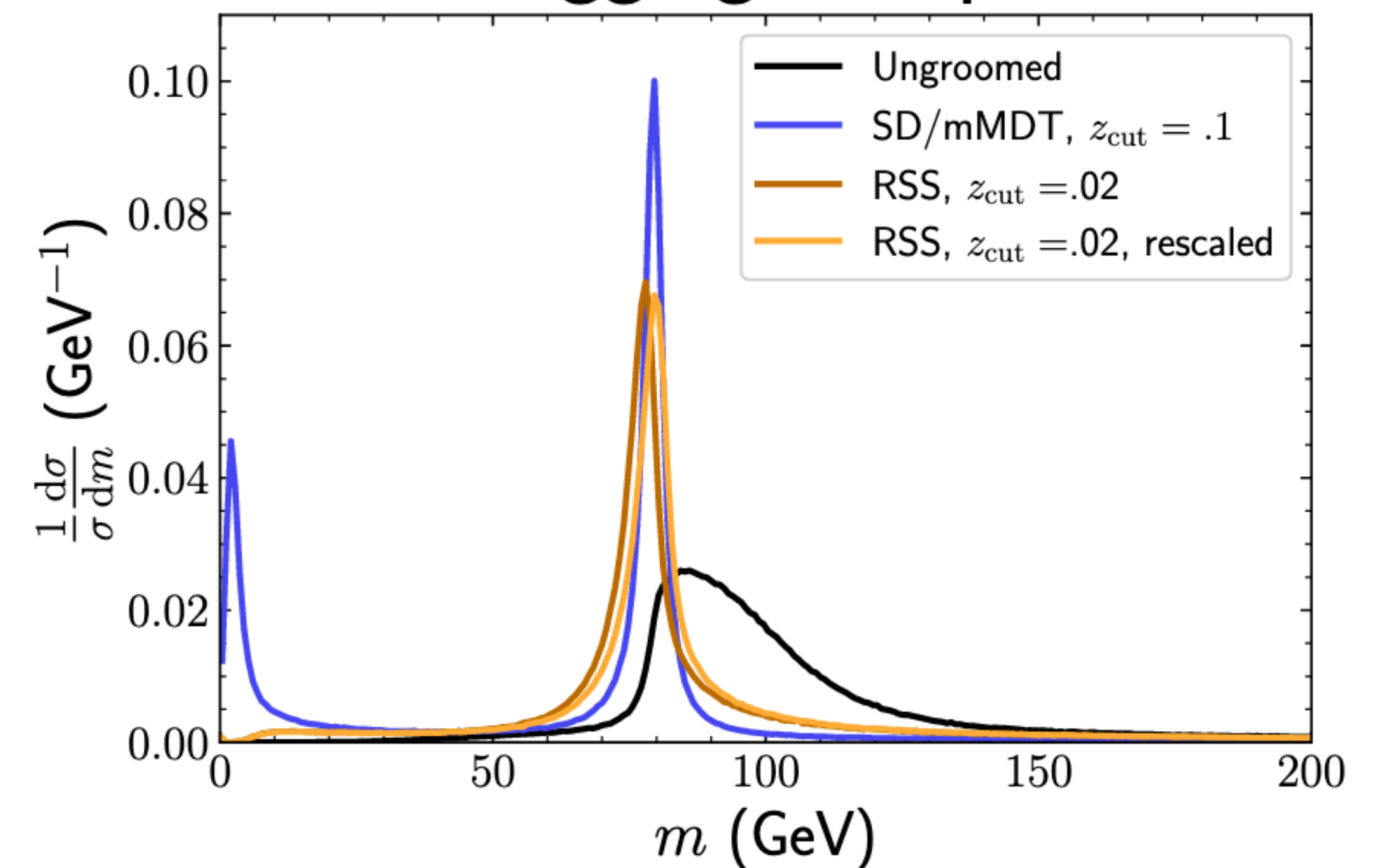
# What comes after soft-drop? ... Recursive Safe Subtraction?

- Improves on soft-drop's sensitivity to hadronisation effects — emissions do not pass/fail grooming due to small changes.



- Degrades W tagging performance (jet mass resolution), but alleviates jets which soft-drop grooms to low mass : better acceptance? Easier to calibrate? How does it compare to existing options?

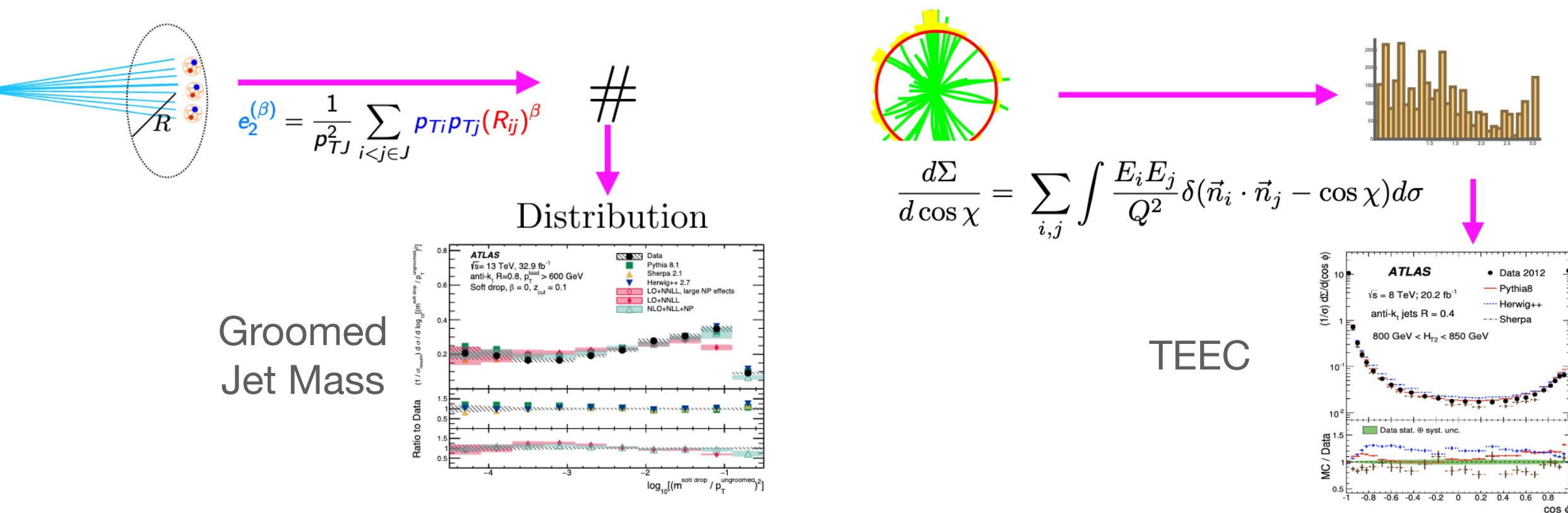
## W Tagging Comparison



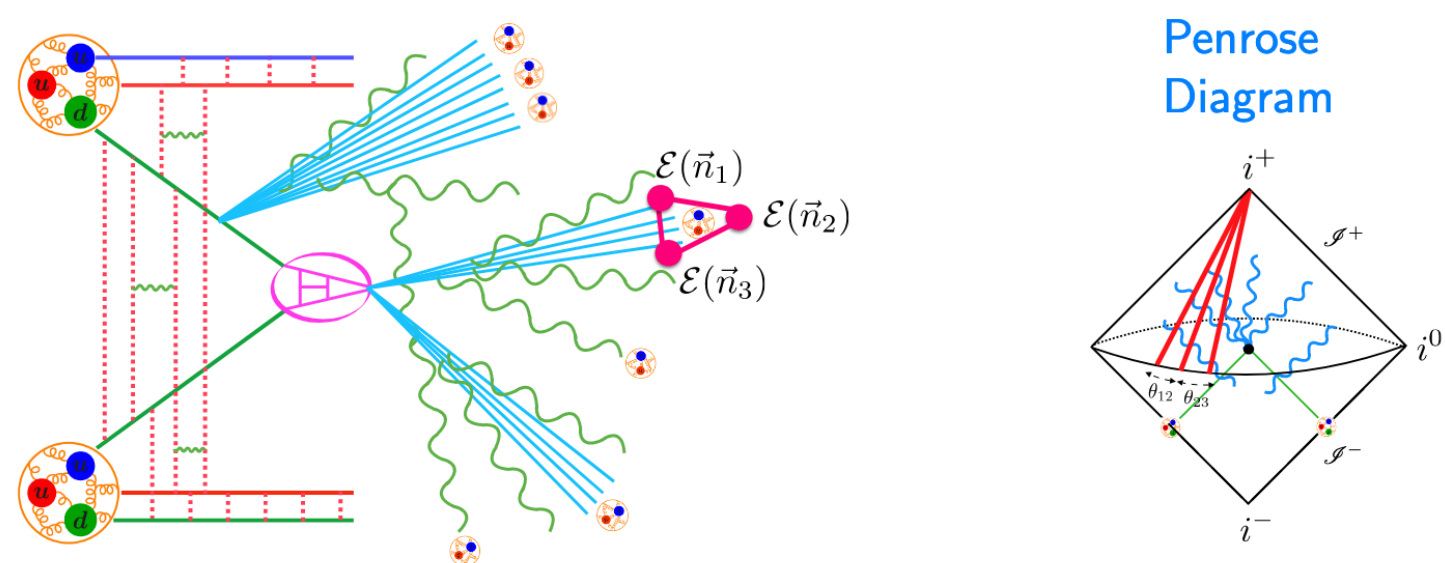
Changing track (functions).

# Energy-energy correlators / weighted cross-sections

- Another point of view which has become very prevalent: to move beyond soft-drop, we should move beyond groomed observables.



- From the theory perspective, weighted cross-sections are “Infinitely Simpler” (Ian means this literally).
- In their collinear limit, energy correlators are jet substructure observables.



## Correlators are Simple

### Correlation Functions

$$\begin{aligned} &\langle E(n_1) \rangle \\ &\langle E(n_1) E(n_2) \rangle \\ &\langle E(n_1) E(n_2) E(n_3) \rangle \\ &\vdots \end{aligned}$$

### Jet Shapes

— Jet mass  
— angularities  
— all standard  
substructure observables

destroys symmetries.

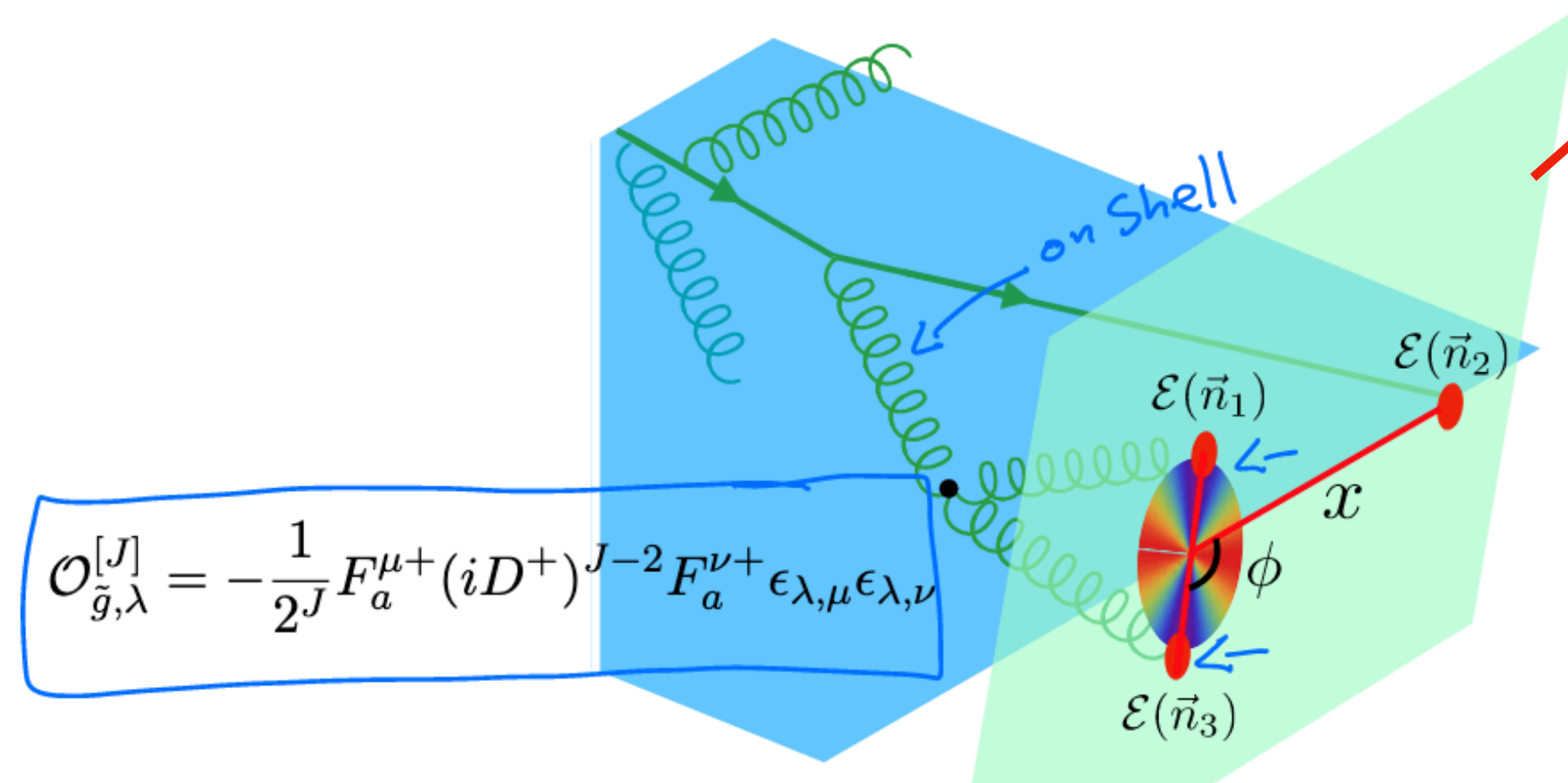
$$m = \langle \delta(m - m[E(n_1), E(n_2)]) \rangle = \sum_{n=0}^{\infty} \delta^{(n)}(m) \langle (m[E(n_1), E(n_2)])^n \rangle$$

- Directly using the fundamental correlators themselves reorganizes our understanding of jet substructure so as to:

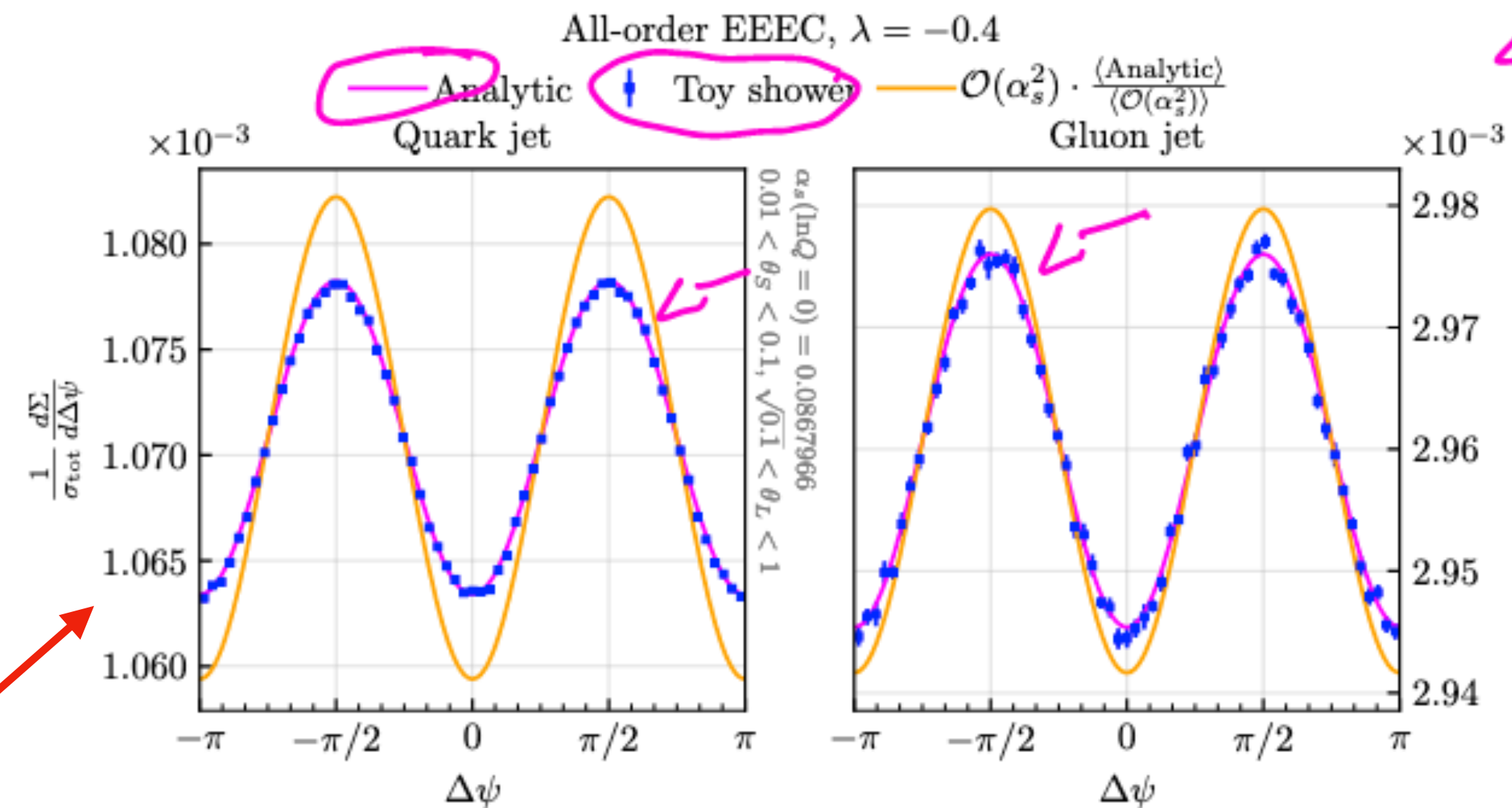
- Exhibit universal scaling behavior.
- Simplify dependence on non-perturbative fragmentation. → See Yibei Li
- Enable the use of powerful symmetries in analytic calculations.

# Energy-energy correlators / weighted cross-sections

- Proposals to utilise higher-point correlators to probe QCD (triple-collinear splitting function), polarized operators.
- In the squeezed limit, the intermediate gluon is nearly on-shell: two polarizations +/- can interfere.



Watch  
Ian's talk  
For the details!!

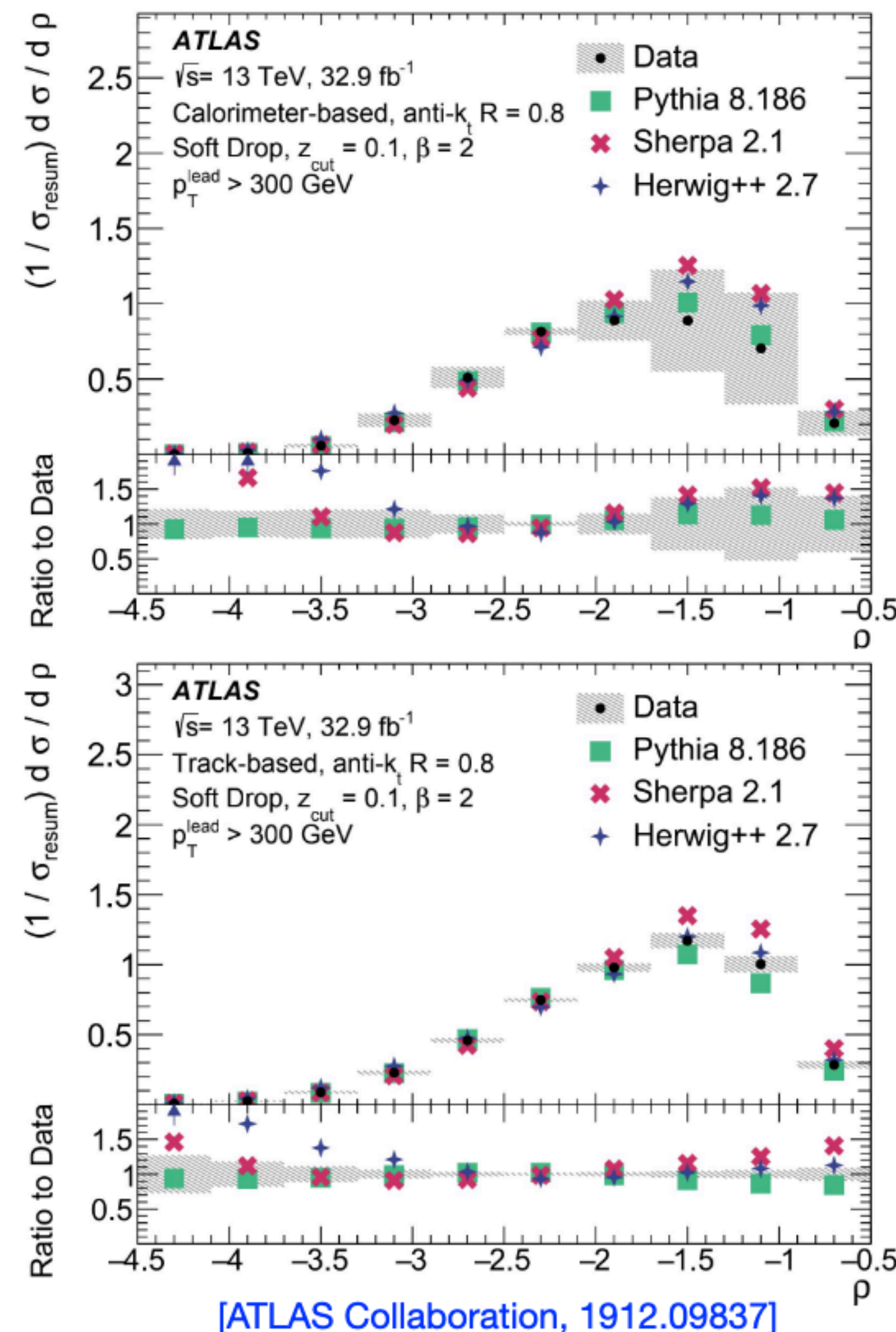


From  
PanScales  
See Talk  
by  
Karlberg.

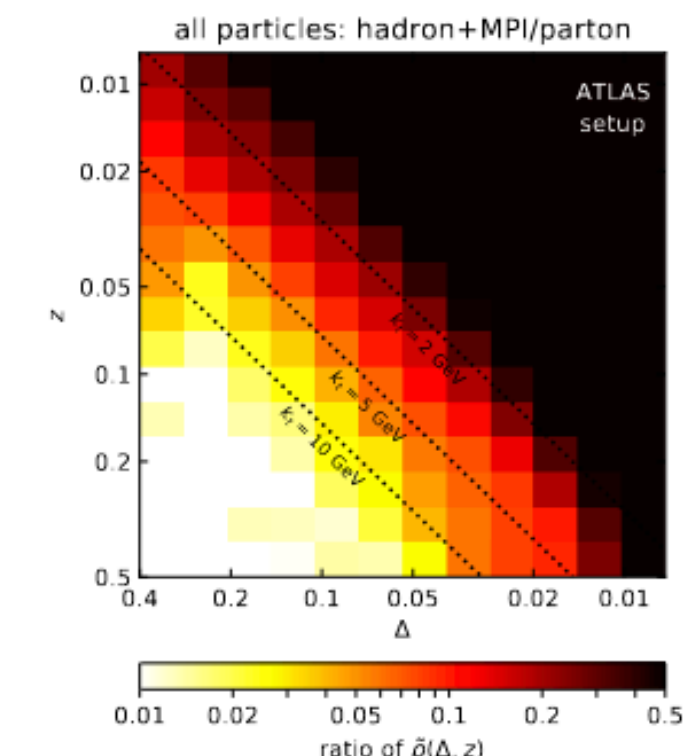
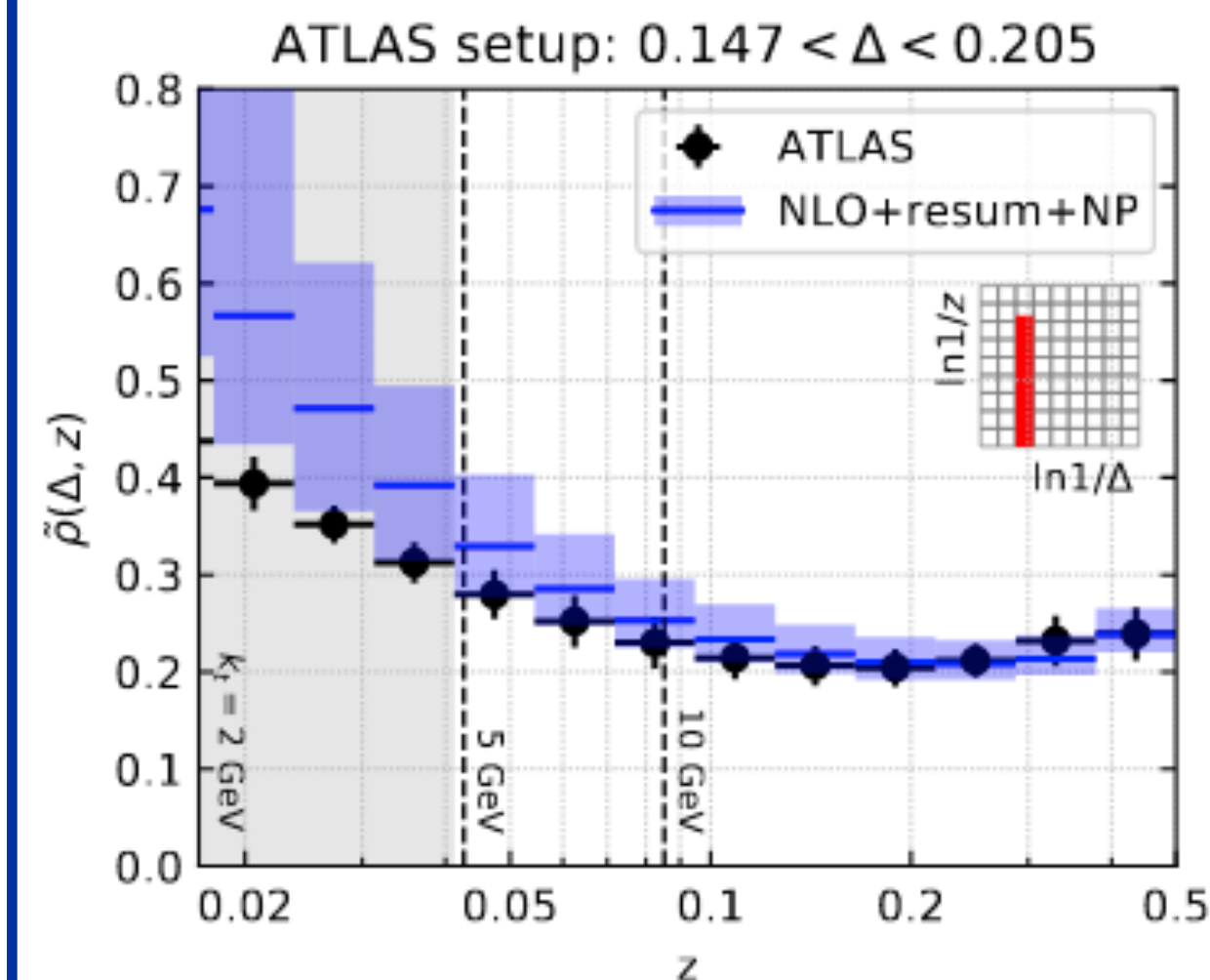
- First analytic resummation including spin interference effects in jets!
- Replicates 'ripple' on power law also observed in PanScales Parton Shower!
- Beautiful interplay between different areas of theory for cross-validation.

# Non-perturbative track functions beyond $\mathcal{O}(\alpha_s)$

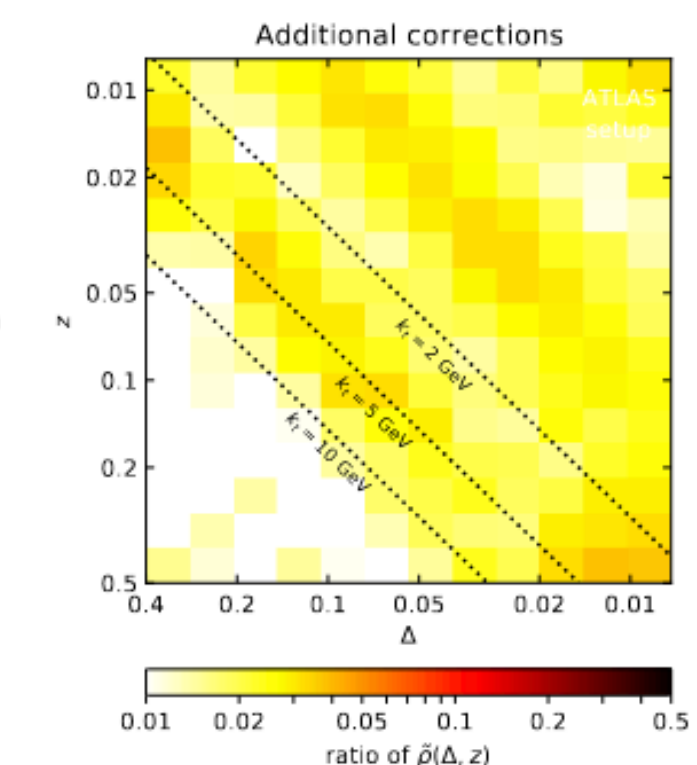
- Measuring EECs within jets requires good angular control: small angles hard to resolve due to finite calor. granularity.
- Experiments have made measurements only using charged particles within jets.
  - Pros:** well-defined systematics, angular resolution, pile-up robust, ...
  - Cons:** No access to neutral component of shower, limited interpretability (not C-safe).
- Q: Could we have it all?
  - A: Yes\*.



- Left:** comparison between ATLAS SD mass measured with (top) calorimeter or (bottom) inner detector signals.
- Below:** comparison between ATLAS LJP measurement (track-based) and analytical prediction + NP correction to charged-particle level.



LJP unc.  
due to  
had./MPI



LJP unc.  
due to  
track  
selection.

# Non-perturbative track functions beyond $\mathcal{O}(\alpha_s)$

- ✓ Track functions introduced and studied at  $\mathcal{O}(\alpha_s)$ .

[H. Chang, M. Procura, J. Thaler, W. Waalewijn, 1303.6637, 1306.6630]

- But very complicated:

observables. For all of these observables, the uncertainties for the track-based observables are significantly smaller than those for the calorimeter-based observables, particularly for higher values of  $\beta$ , where more soft radiation is included within the jet. However, **since no track-based calculations exist at the present time**, calorimeter-based measurements are still useful for precision QCD studies. [ATLAS Collaboration, 1912.09837]

the selection of charged particle jets. Note that track-based observables are IRC-unsafe. In general, nonperturbative track functions can be used to directly compare track-based measurements to analytical calculations [67–69]; **however, such an approach has not yet been developed for jet angularities**. Two techniques are used, described in the following subsections, to apply the nonperturbative corrections.

[ALICE Collaboration, 2107.11303]

- ✓ This talk: Establish track function formalism beyond leading order.

**Precision calculation for tracks now possible!**

- ◆ **New insights:**

- ▶ Energy correlators are much simpler to interface with track functions.
- ▶ Moments of track functions have simple evolution.

allowing  **higher order calculation**

3

[1303.6637]

- For a  $\delta$ -function type observable  $e$  measured using partons:

$$\frac{d\sigma}{de} = \sum_N \int d\Pi_N \frac{d\sigma_N}{d\Pi_N} \delta \left[ e - \hat{e}(p_i^\mu) \right]$$

↓ tracks

$$\frac{d\sigma}{d\bar{e}} = \sum_N \int d\Pi_N \frac{d\bar{\sigma}_N}{d\Pi_N} \int \prod_{i=1}^N dx_i T_i(x_i) \delta \left[ \bar{e} - \hat{e}(x_i p_i^\mu) \right]$$

full functional form of T

- For an energy correlator at partonic level: e.g. 2-point correlator (EEC)

$$\frac{d\Sigma}{d\cos\chi} = \sum_{i,j} \int \frac{E_i E_j}{Q^2} \delta \left( \cos\chi - \cos\chi_{ij} \right) d\sigma$$

$$E_i^n \rightarrow \int dx_i T_i(x_i) x_i^n E_i^n$$

$$= T_i(n) E_i^n$$

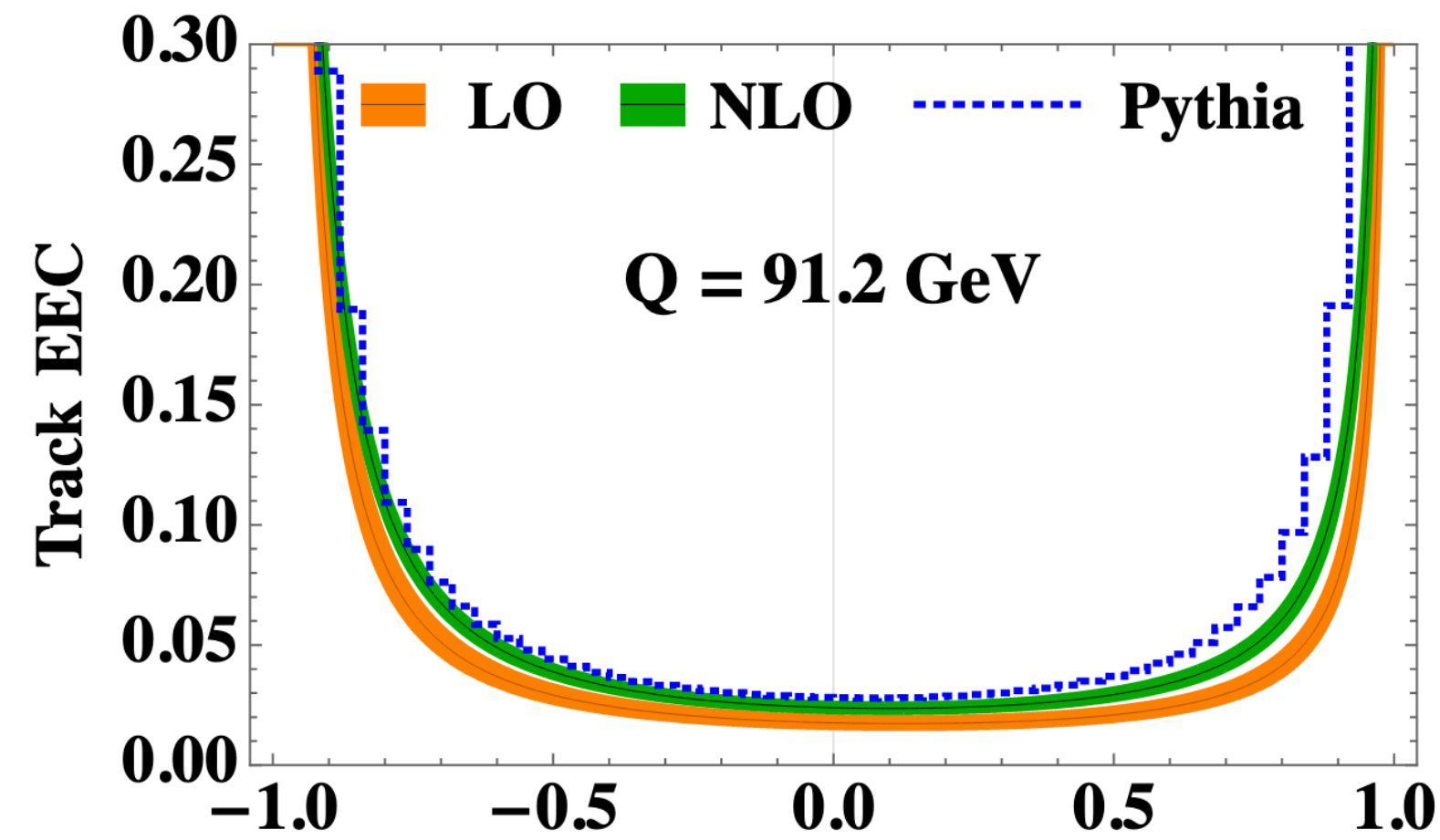
Mellin moments

only moments of T

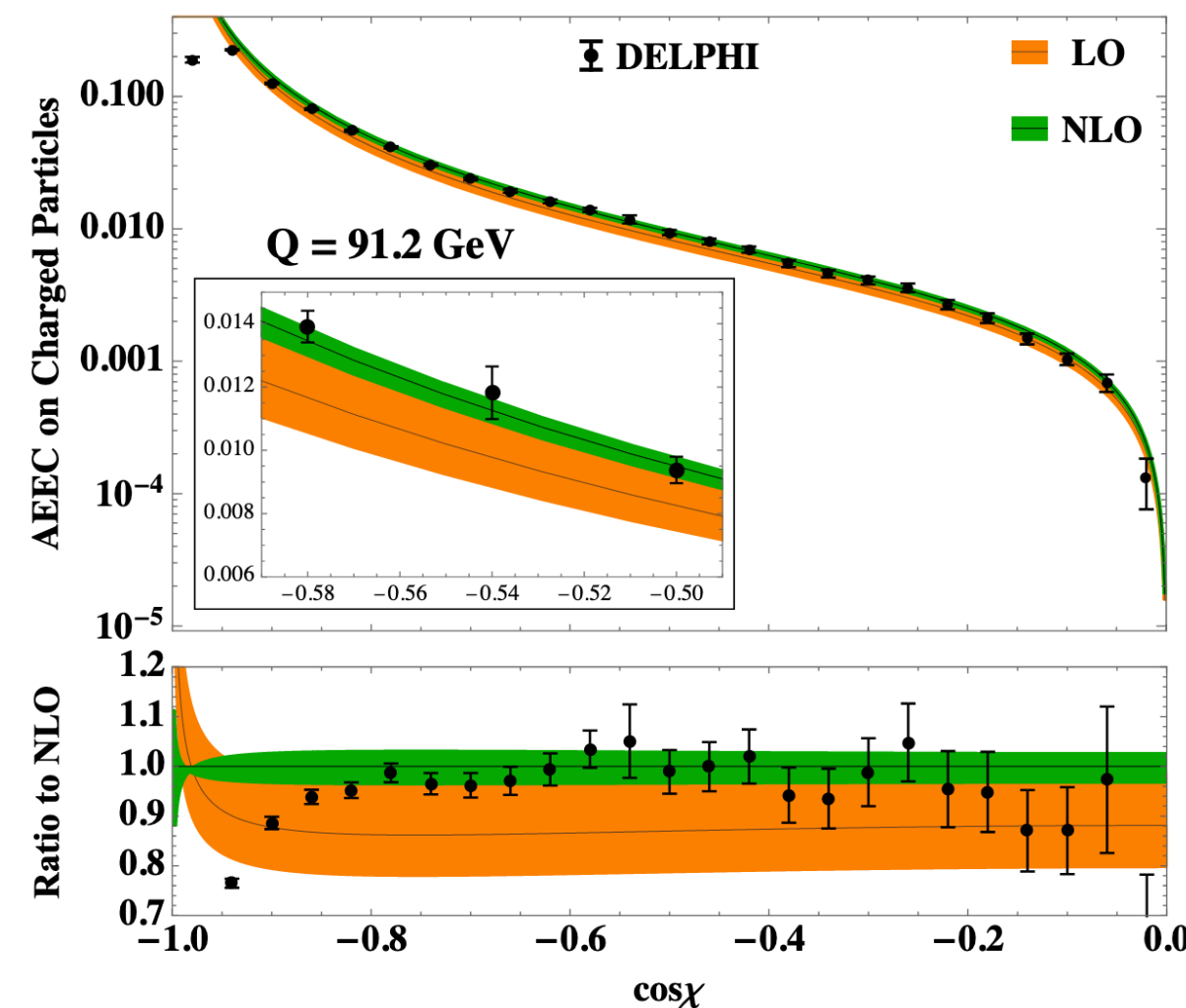
$$\left( \frac{d\Sigma}{d\cos\chi} \right)_{\text{tr}} = \sum_{i,j} T_i(1) T_j(1) \int \frac{E_i E_j}{Q^2} \delta \left( \cos\chi - \cos\chi_{ij} \right) d\bar{\sigma}$$

**Track EEC**

- First NLO ( $\mathcal{O}(\alpha_s^2)$ ) calculations for track-based observables
- Results are available in completely analytical form.



- $\text{AEEC}(\cos \chi) = \text{EEC}(\cos \chi) - \text{EEC}(-\cos \chi)$ ,  $\cos \chi \leq 0$



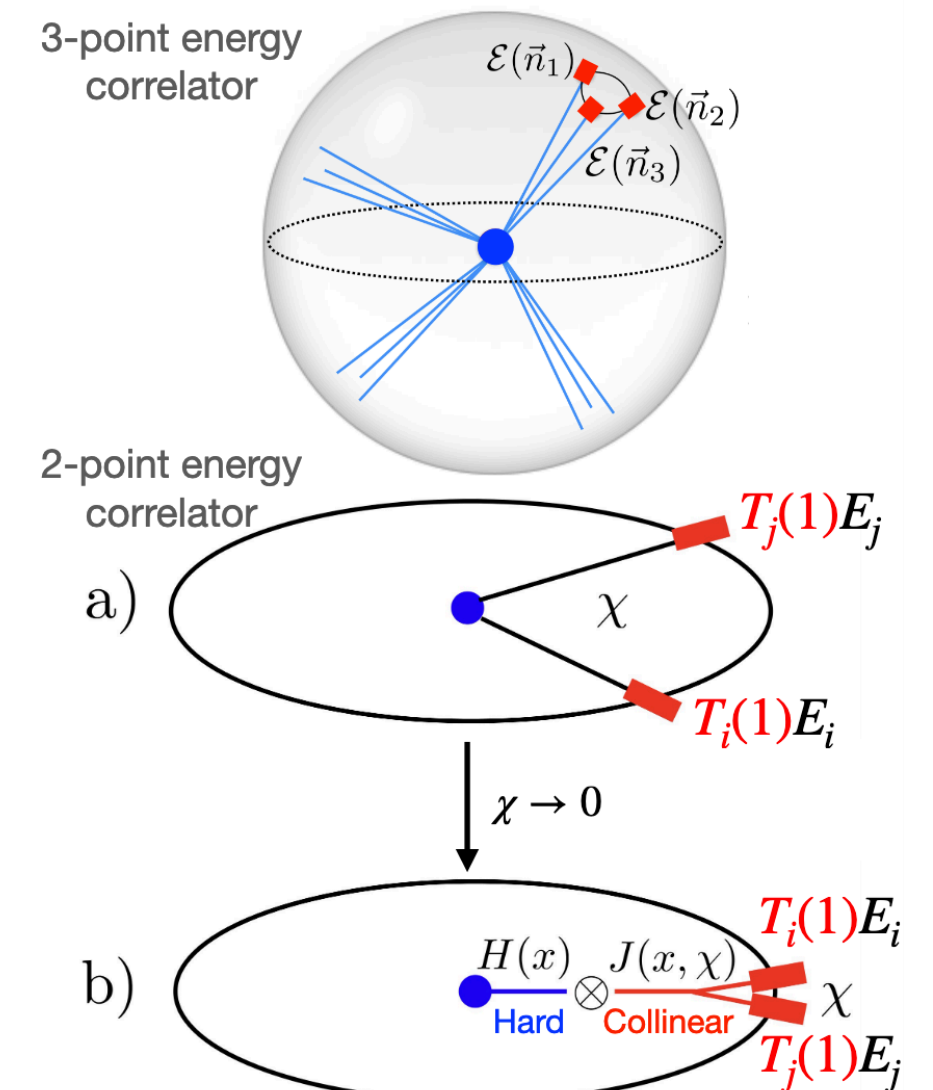
## Jet Substructure

### In the collinear limit:

- The energy correlator is a jet substructure observable.
- Jet function constants (jet functions with the logarithmic dependence excluded):
  - The moments  $T_i(n)$  appear as the coefficients.
  - e.g. for track EECs, up to  $\mathcal{O}(\alpha_s^2)$

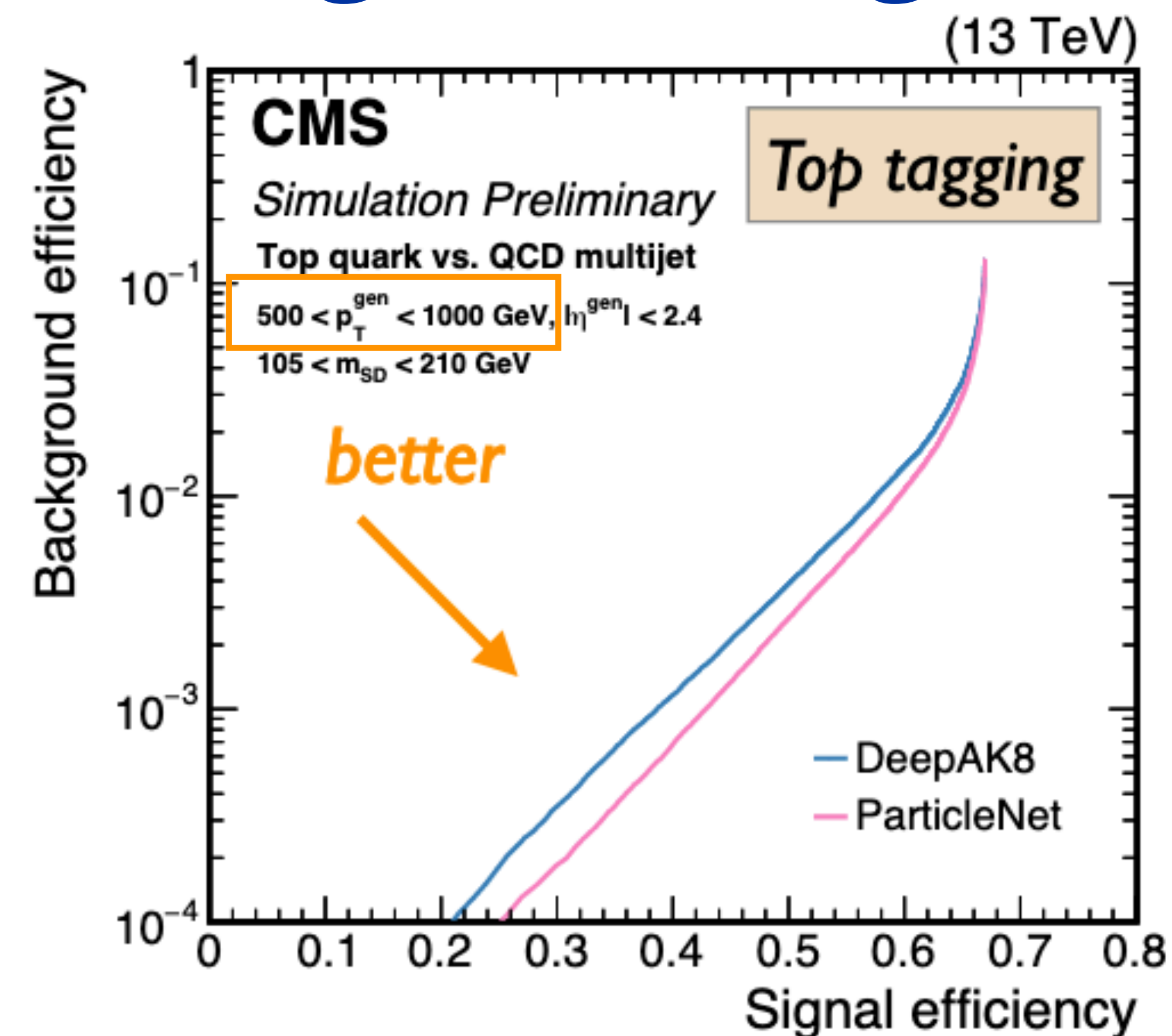
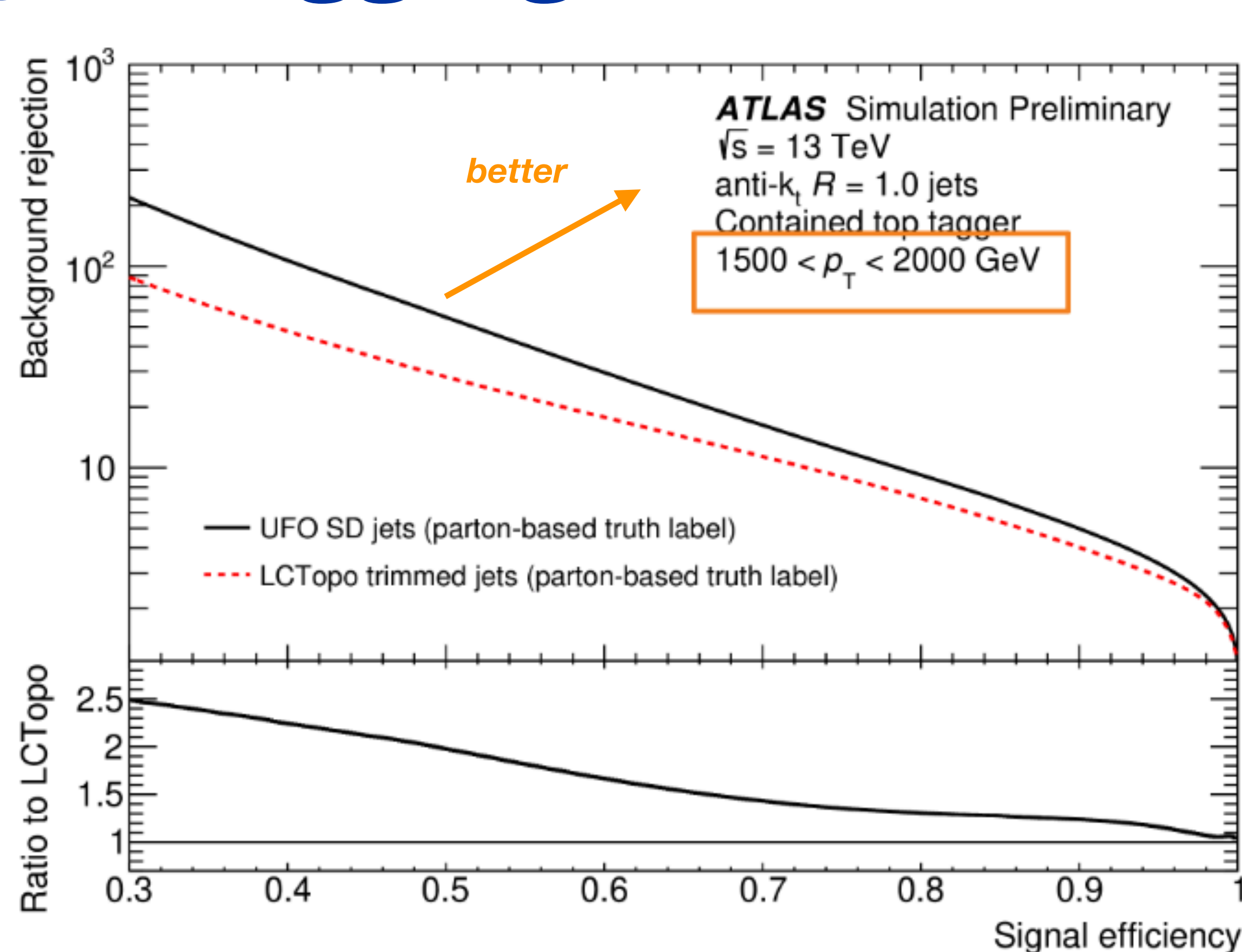
$$j^g = \frac{1}{4} T_g(2) + a_s \left\{ T_g(1) T_g(1) C_A \left( -\frac{449}{150} \right) + \sum_q T_q(1) T_{\bar{q}}(1) T_F \left( -\frac{7}{25} \right) \right\} \\ + a_s^2 \left\{ T_g(1) T_g(1) \left\{ C_A^2 \left( -\frac{527\zeta(3)}{10} + \frac{133639871}{3240000} - \frac{2159\pi^2}{1800} + \frac{19\pi^4}{90} \right) + C_A n_f T_F \frac{139}{270} \right\} + \sum_q T_q(1) T_{\bar{q}}(1) \dots \right\}$$

- Matches the state-of-the-art calculation for jet substructure, but now on tracks!  
[Kardos, Larkoski, Trocsanyi, 2002.05730]



Are ATLAS & CMS ...  
BOOSTing apart?

# Jet Tagging : ATLAS & CMS Strategies Diverge

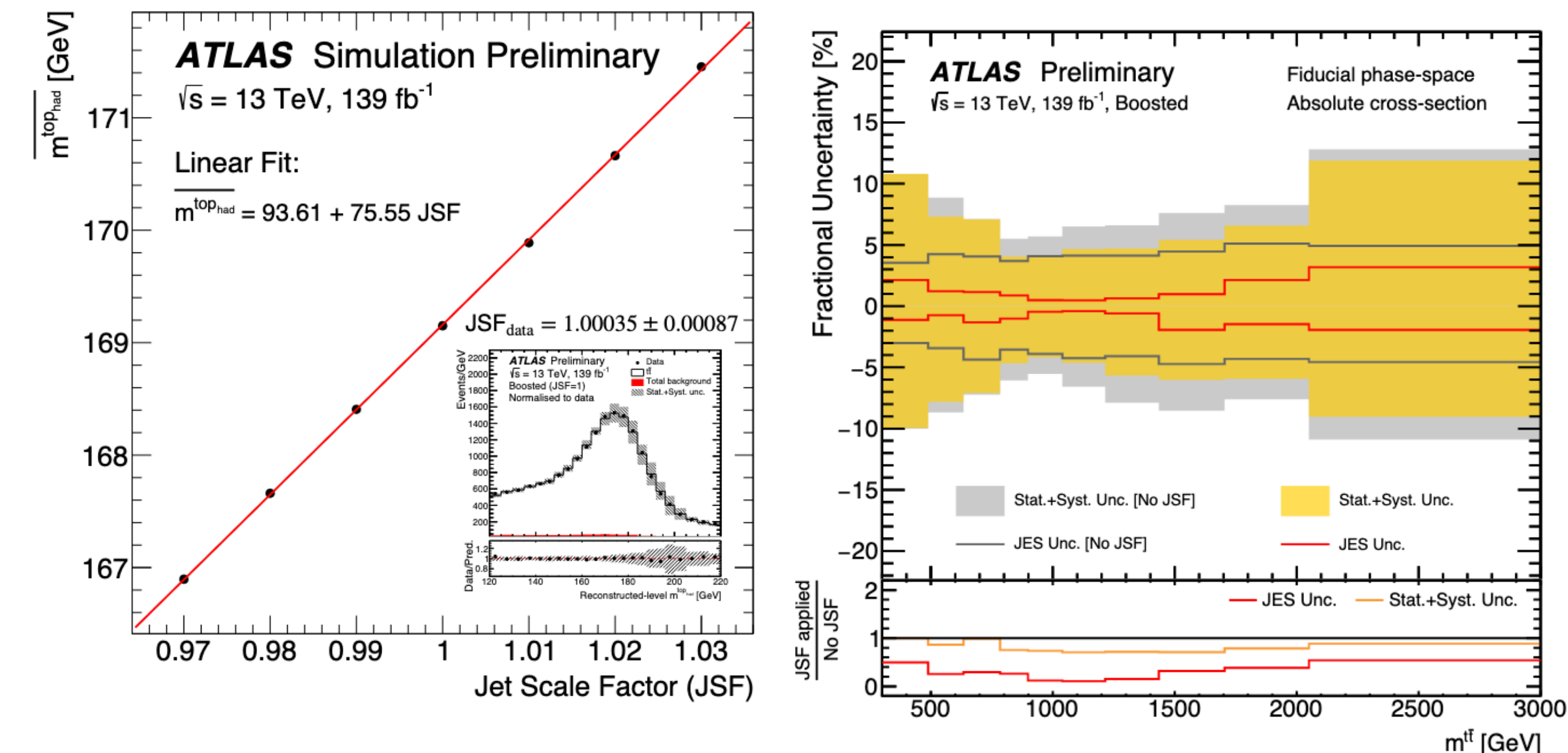


**Different jet inputs (Track+Calo objects, cluster splitting)**

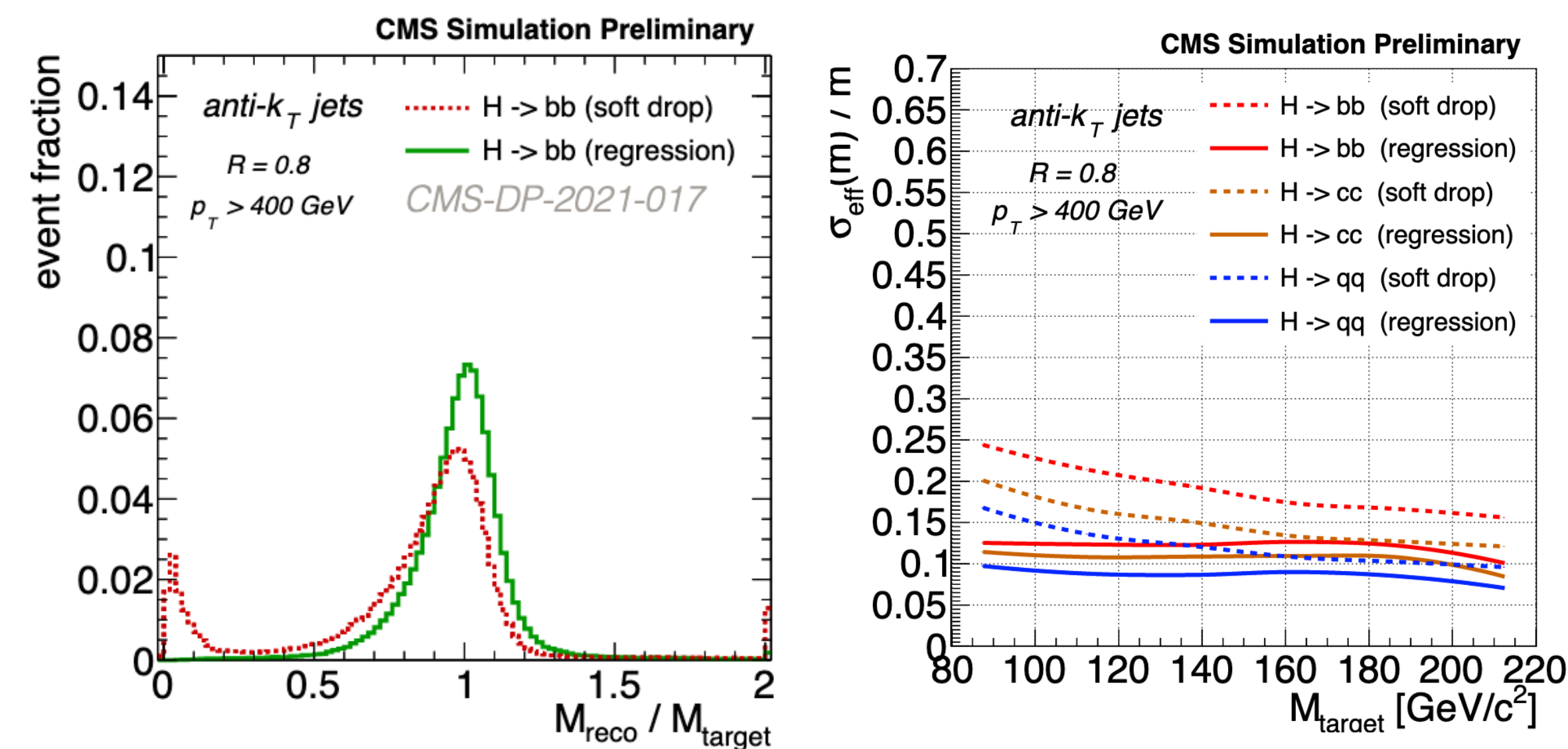
**Different architecture (Graph NN vs. Deep NN)**

- Big improvements to boosted object tagging on display from both ATLAS and CMS, but via completely different approaches! (Do not directly compare these plots to each-other!)

# Jet Calibration : ATLAS & CMS Strategies Diverge



*Auxiliary measurements in top cross-sections*

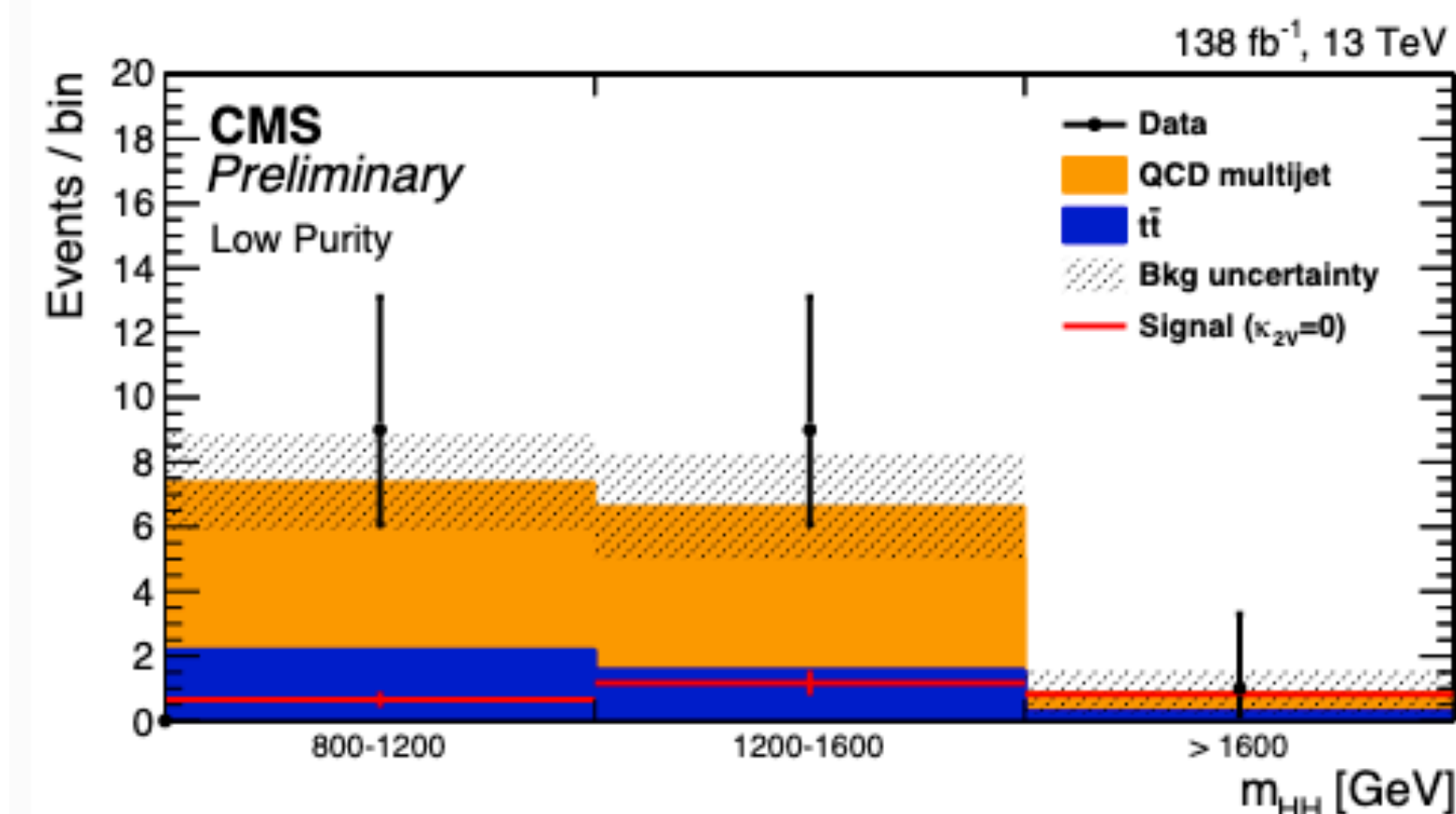
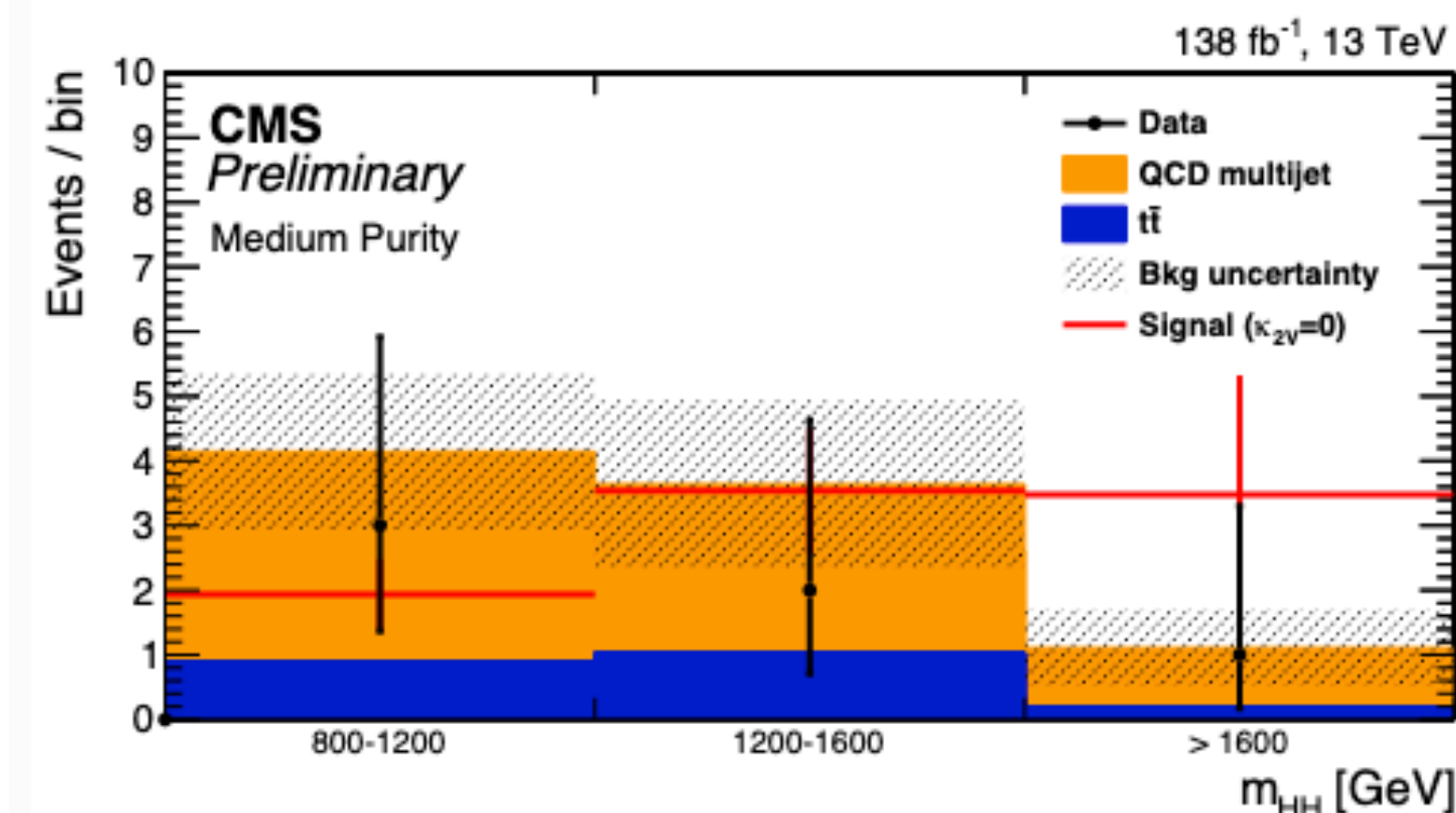
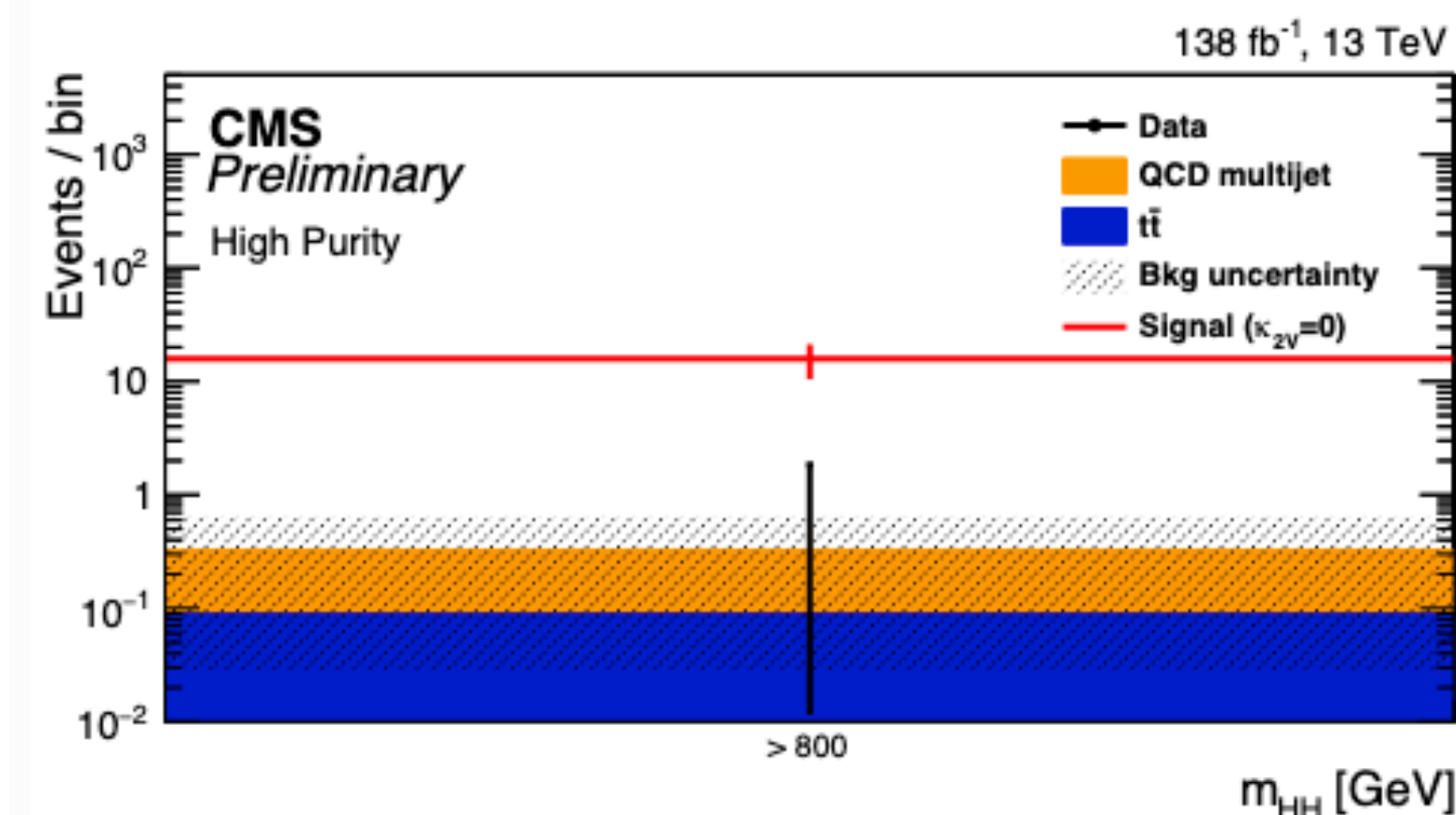
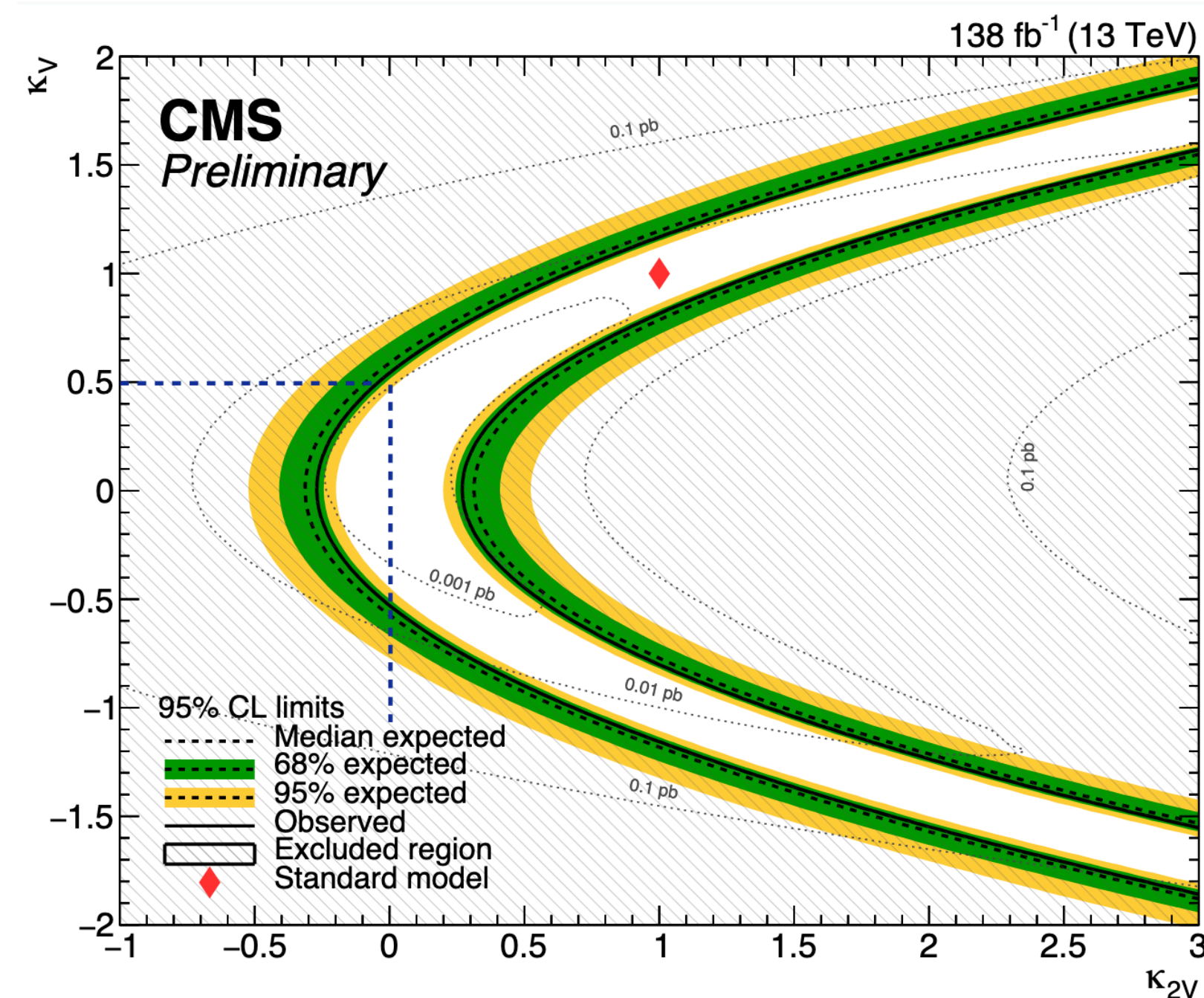
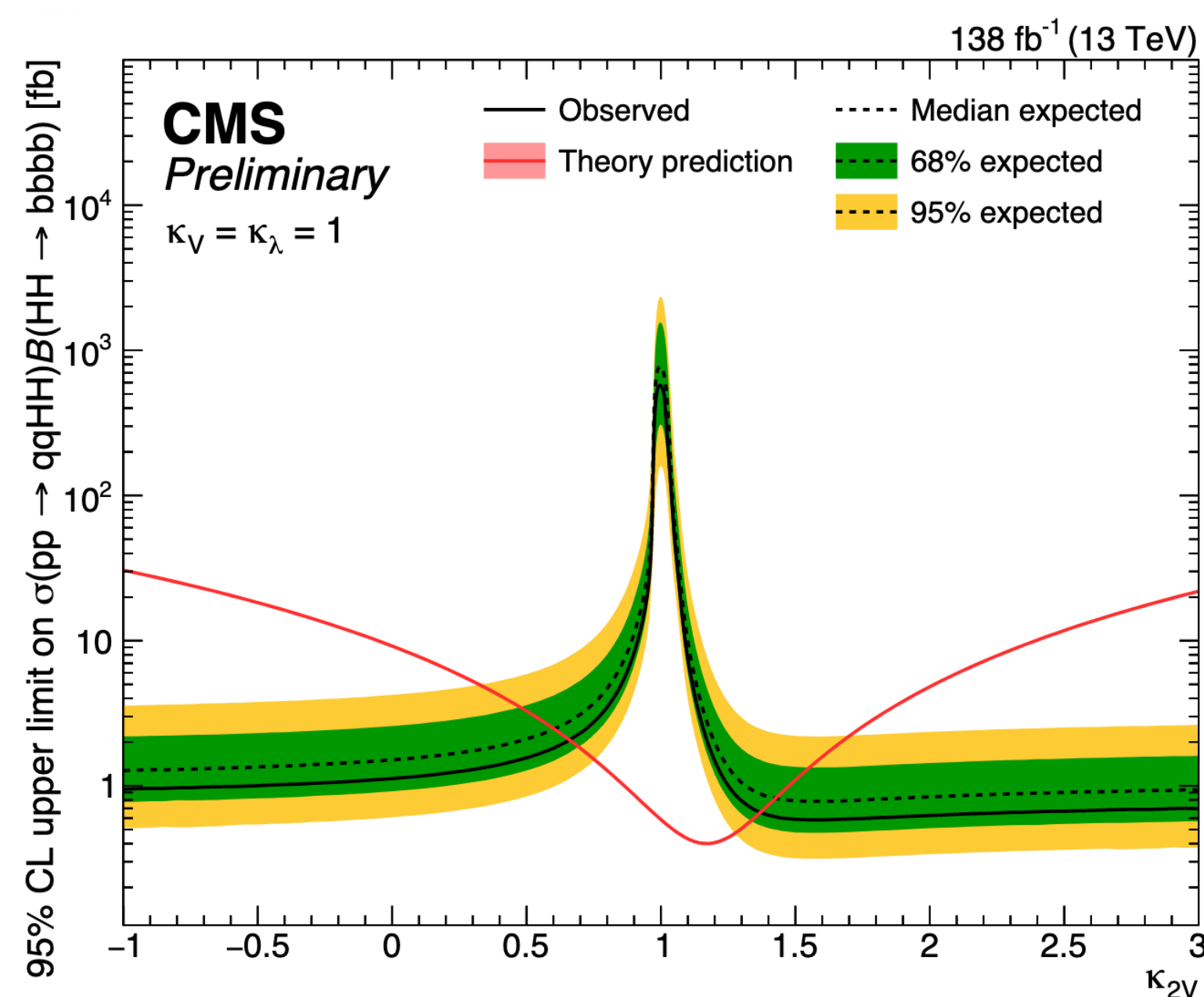


*Mass regression for boosted Higgs bosons*

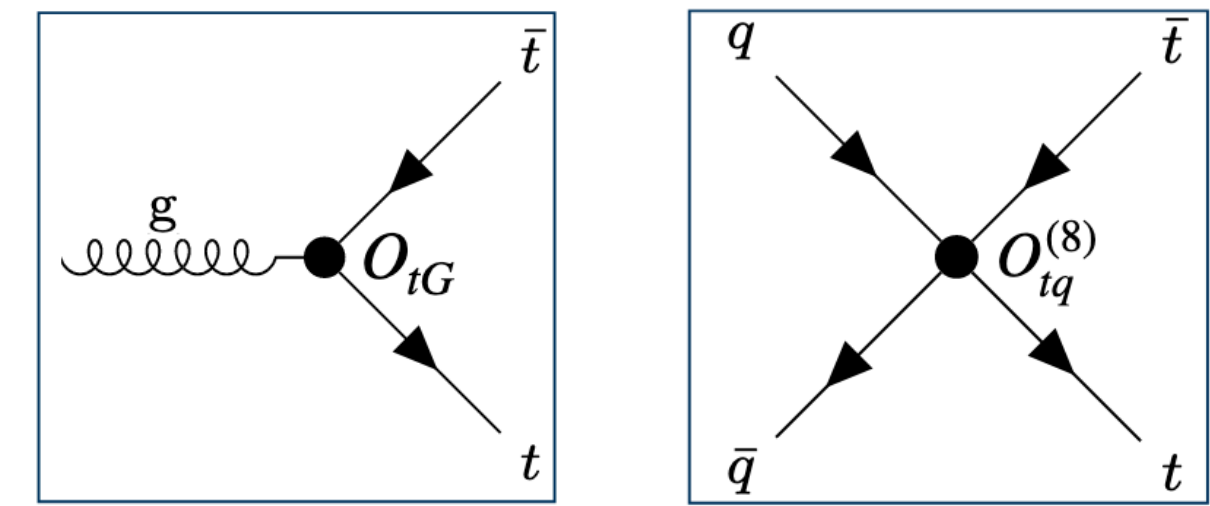
- ATLAS and CMS calibration strategies are also quite different: auxiliary measurements to constrain the jet energy scale in top cross-sections increase precision, but so do DNNs!

# CMS BOOSTs VBF $HH \rightarrow 4b$ ( $\kappa_{2V}$ )

- VBF di-Higgs production is uniquely sensitive to  $VHh$  coupling ( $\kappa_{2V}$ ).
- In scenarios where this coupling is anomalous, the H bosons can become boosted.
  - Reduces combinatorics.
  - Small SM background at high  $m_{HH}$ .
- QCD background data-driven,  $t\bar{t}$  taken from simulation.



# ATLAS BOOSTs EFTs with top quarks



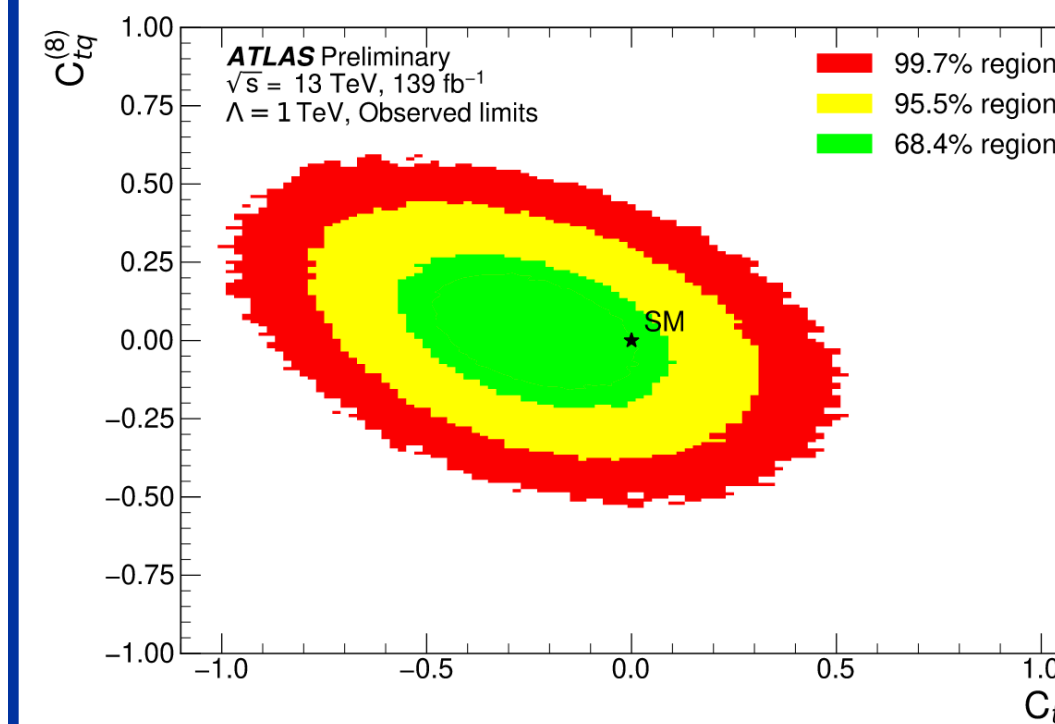
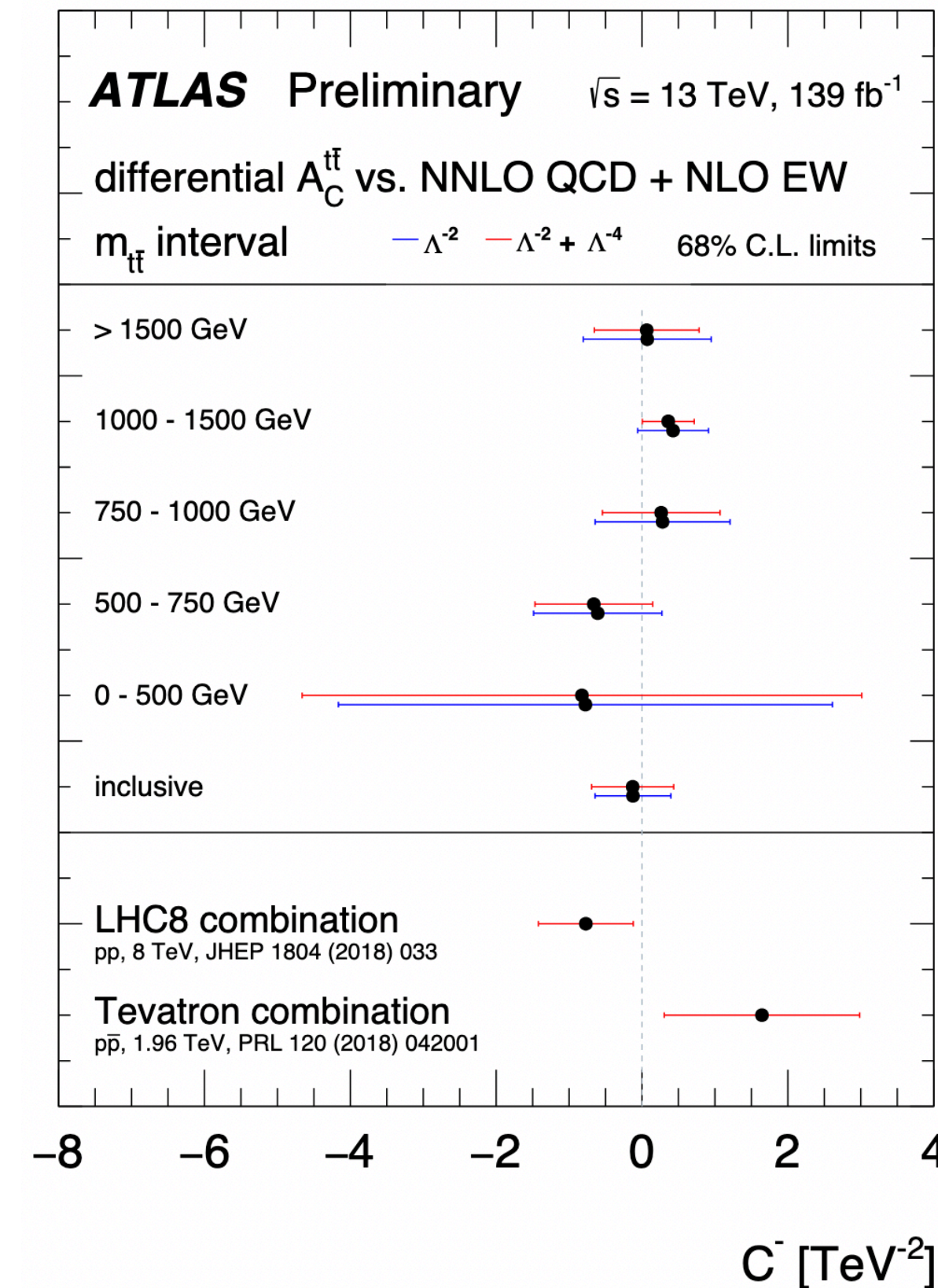
- **Top pair charge asymmetry measurement** is sensitive to many four-fermion EFT operators.

- Reduced to C- via linear combination.

- EFT sensitivity grows with  $m_{t\bar{t}}$ .

- Very precise  $>1500$  GeV bin & incl. measurement improve on previous constraints.

- Nicely illustrates the power of increasing the LHC dataset size.



Wilson coefficient	Marginalised 95% CL		
	Expected	Observed	
$C_{tG}$	[-0.44, 0.44]	[-0.68, 0.21]	
$C_{tq}^{(8)}$	[-0.35, 0.35]	[-0.30, 0.36]	

Wilson coefficient	Individual 95% CL		
	Expected	Observed	Global fit [1]
$C_{tG}$	[-0.41, 0.42]	[-0.63, 0.20]	[0.007, 0.111]
$C_{tq}^{(8)}$	[-0.35, 0.36]	[-0.34, 0.27]	[-0.40, 0.61]

- New differential lepton+jets cross-section measurement, applied to constrain two dim-6 EFT operators.
- Also incorporates an interesting auxiliary measurement technique to constrain the jet energy scale / resolution uncertainty.

The Lund jet plane seems  
here to stay.

# Lund jet plane

QCD radiation within jets  
is approx. uniform in  
 $\ln(E), \ln(\theta)$ :

$$P(E, \theta) = \frac{2\alpha_s C_g}{\pi} \frac{1}{E\theta} e^{-\frac{\alpha_s C_g}{\pi} \ln^2 E\theta}$$

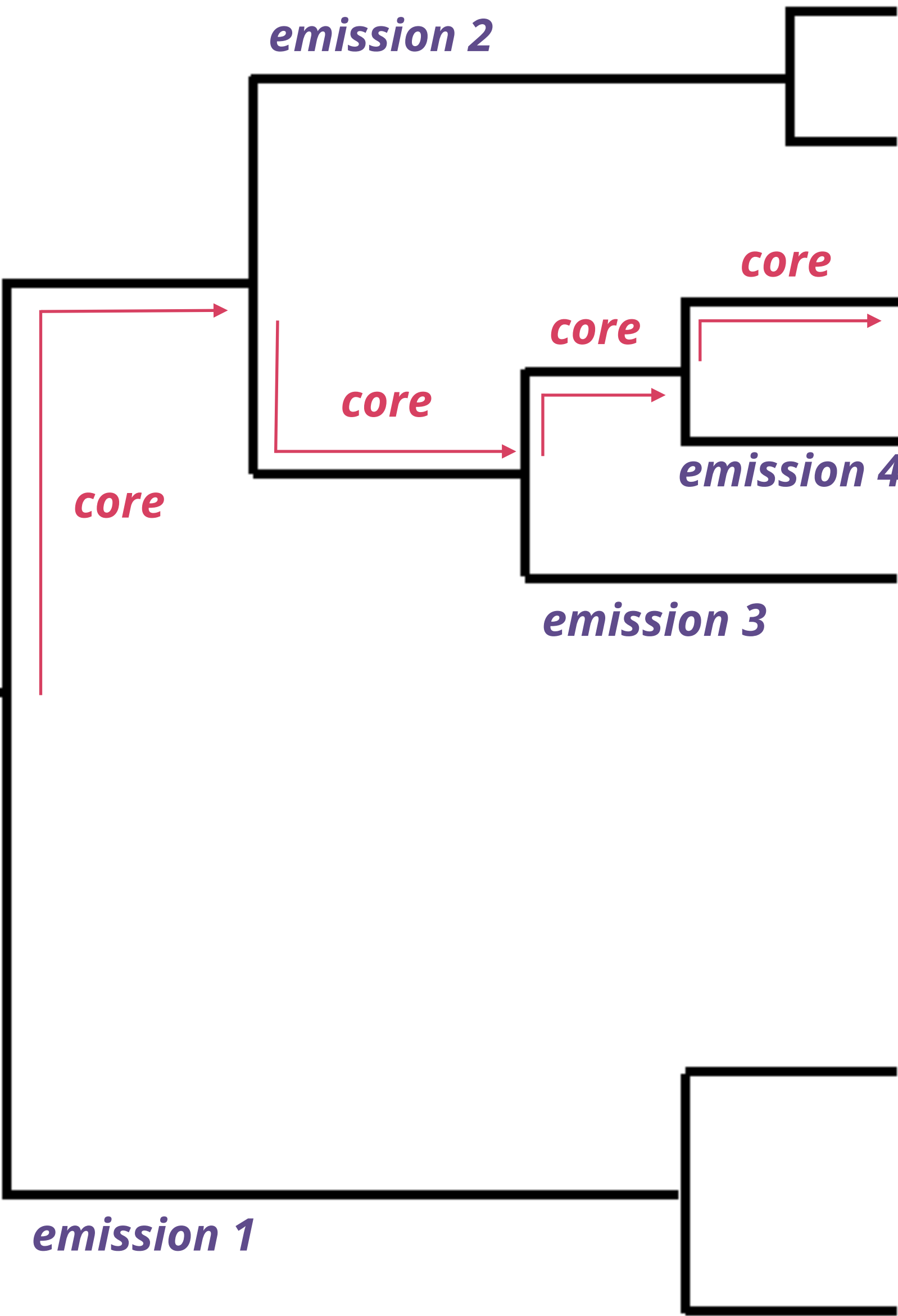
$j$

## 1. C/A Reclustering:

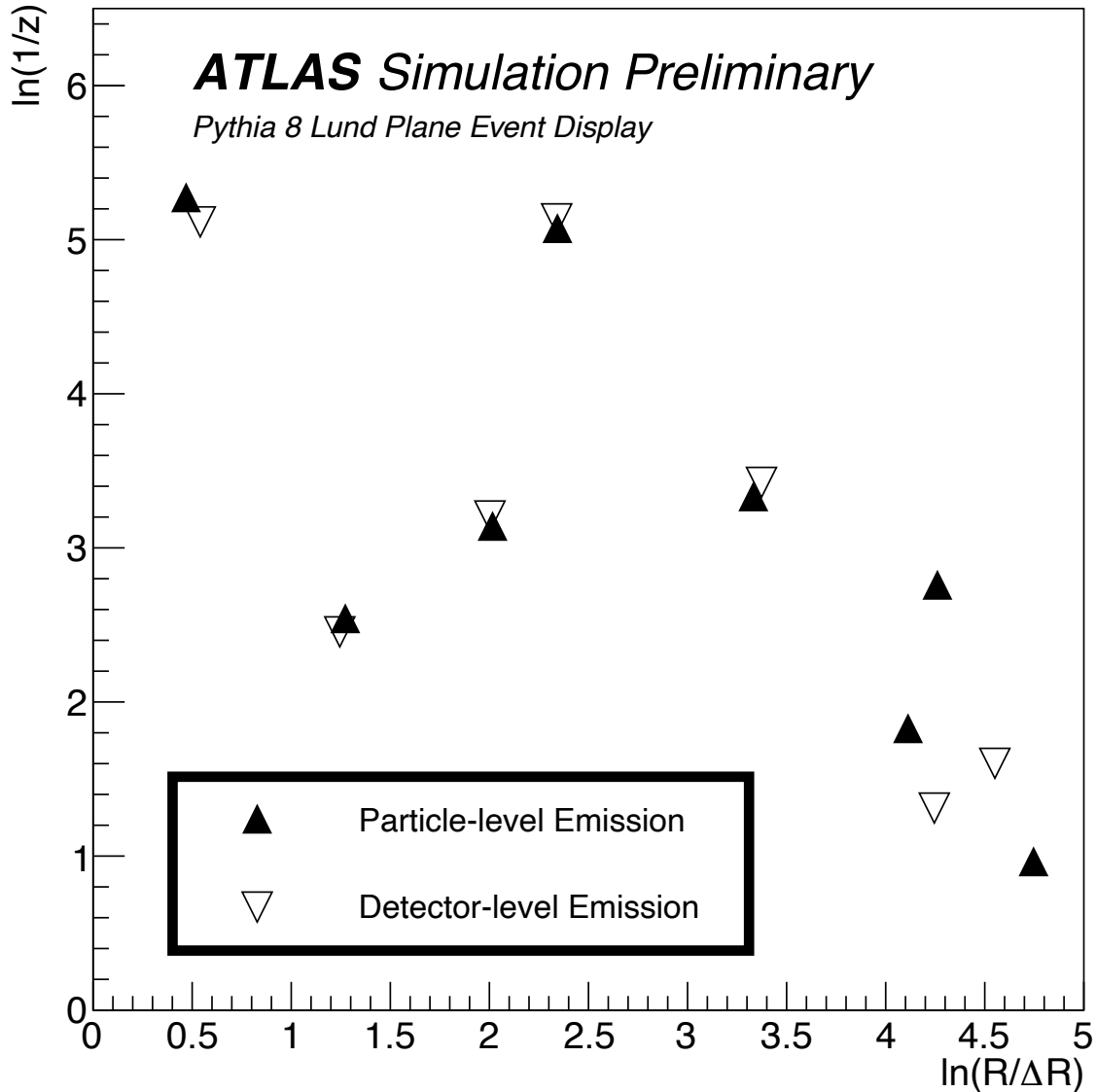
Combine closest pairs  
of **charged particles or  
tracks!**

## 2. C/A Declustering:

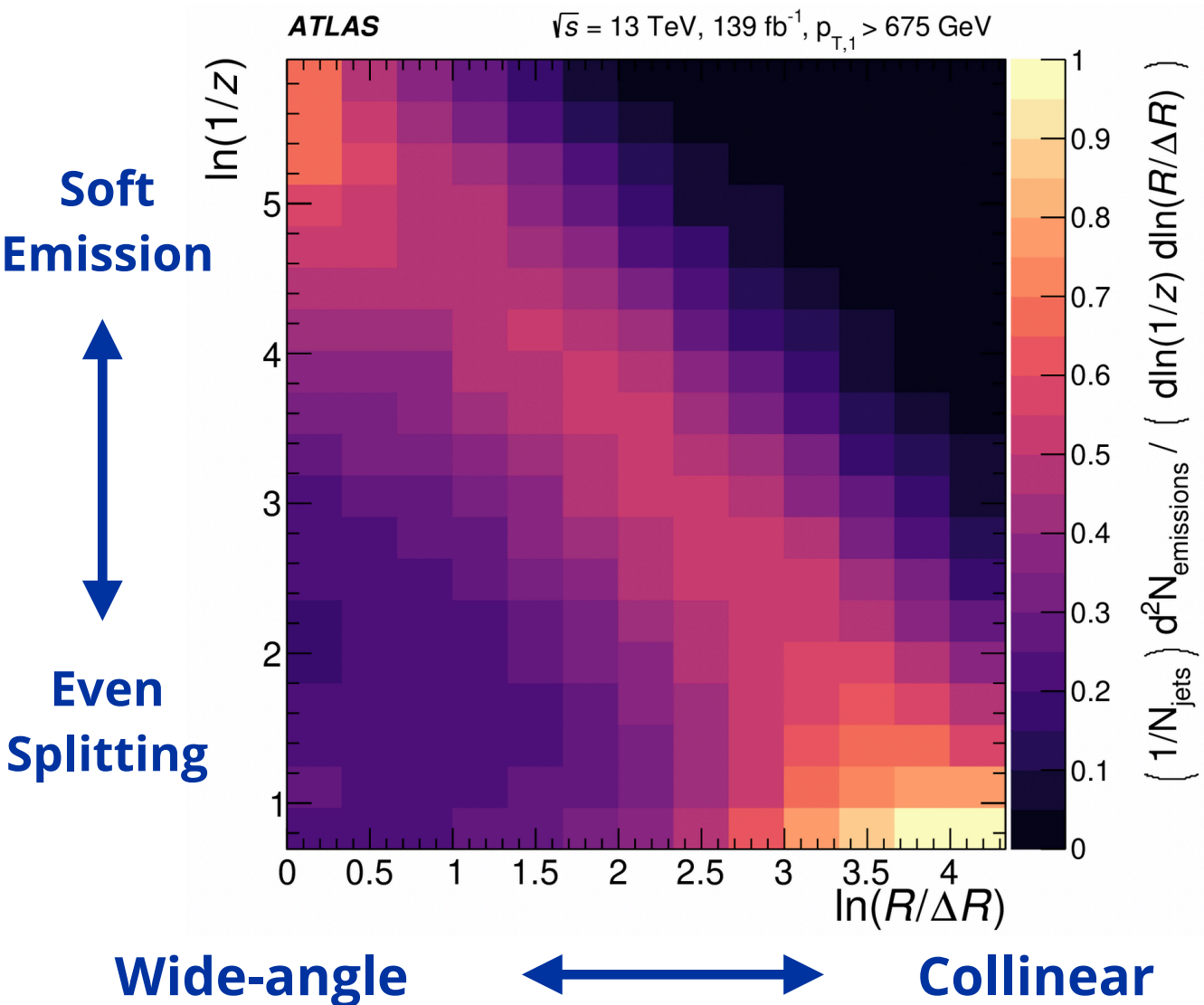
Unwind, widest angles first.  
Each step is an **emission**, or,  
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A single jet results in **a set of  
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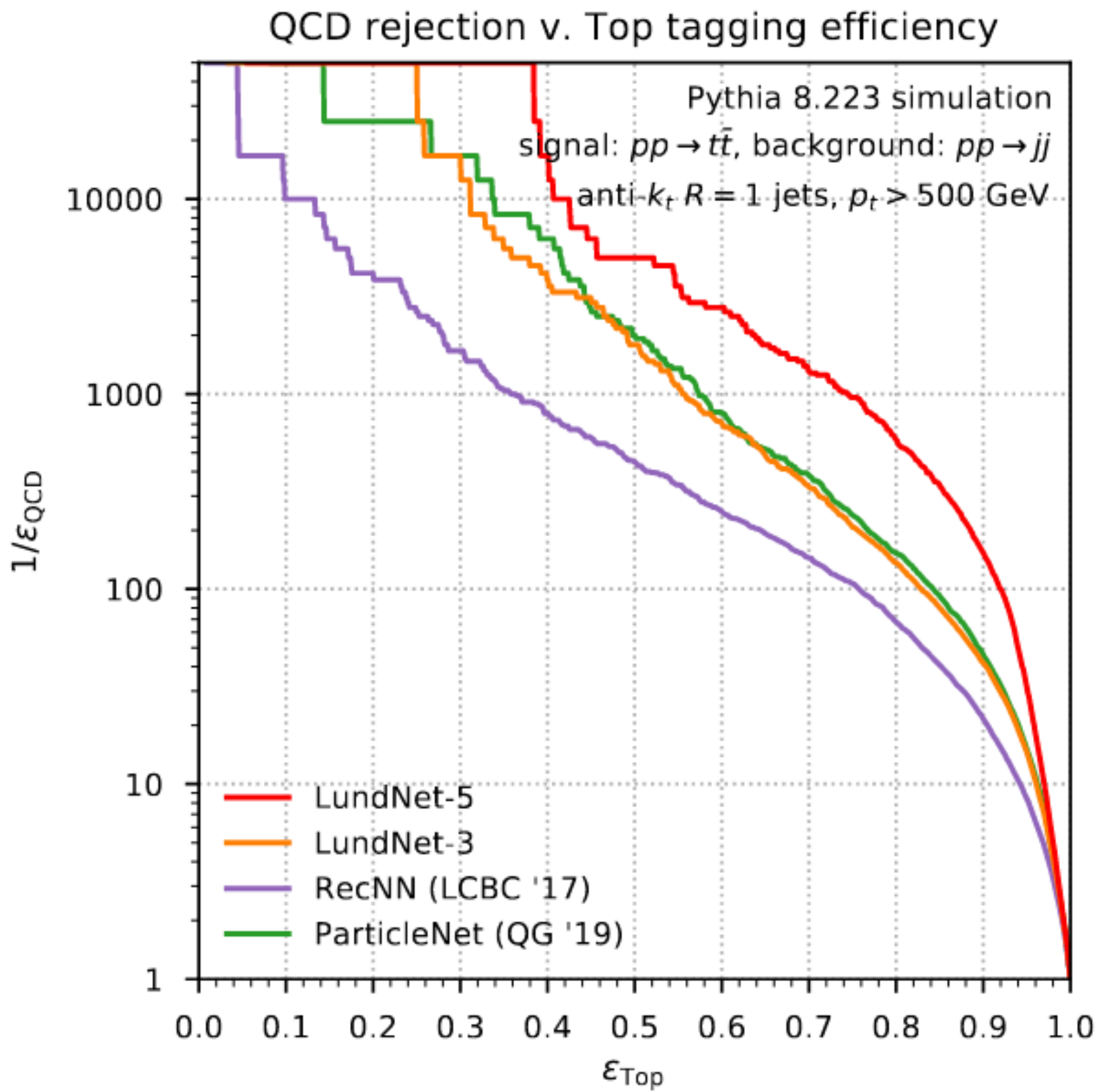


# Lund GNNs

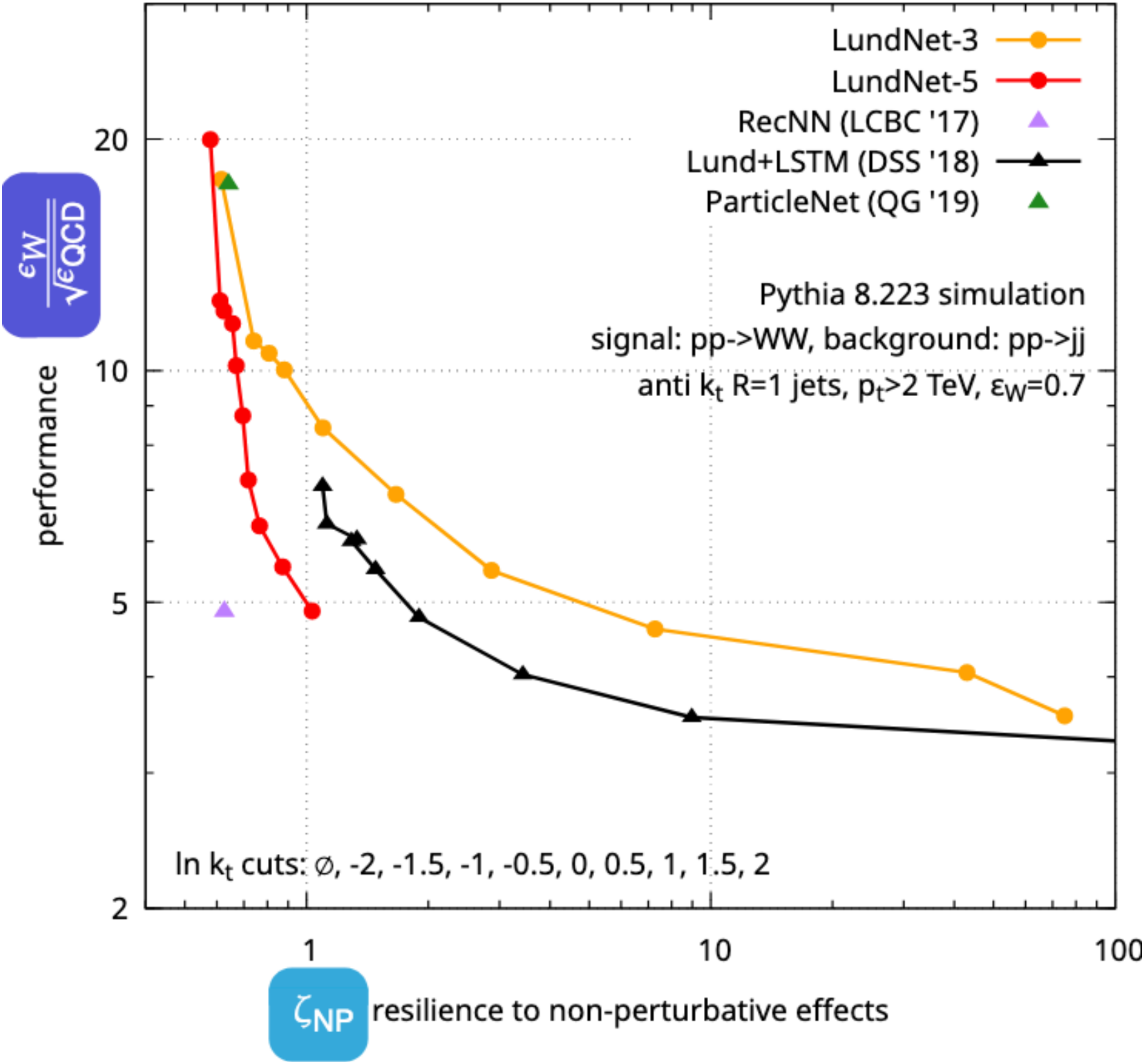
- Graph networks (GNNs) have proven to be very powerful tools for boosted object tagging at the LHC (CMS).
- ... is there some advantageous way to present a jet to such a network?
  - Studies training GNNs with LJP-tuples.
- Interesting question: how many degrees of freedom are there in a jet\*? How much redundant information is helpful to provide?

**LundNet-5** :  $(\ln k_t, \ln \Delta, \ln z, \ln m, \psi)$

**LundNet-3** :  $(\ln k_t, \ln \Delta, \ln z)$



- Lund-jet-plane-graph-networks seem to outperform some versions of ParticleNet.



- ML methods tend to be sensitive to non-perturbative effects: the more performant options are the least ‘resilient’ to hadronisation (and detector) effects.

\* A jet with  $N$  particles has a phase space that is  $3N-4$  dimensional.  
However, the information that the LundNet5 keeps is something like  $5N-5$  dimensional

# ALICE LJP

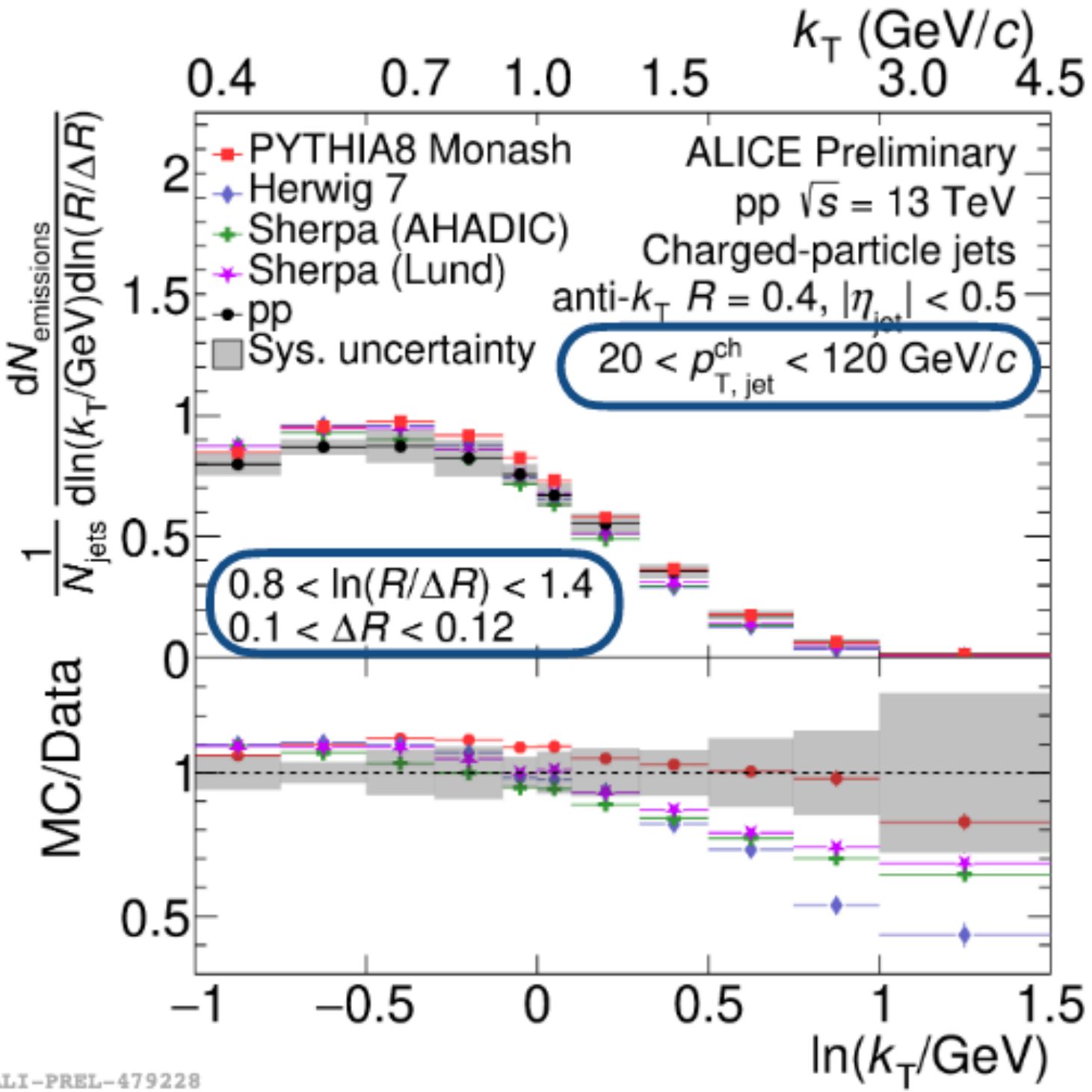
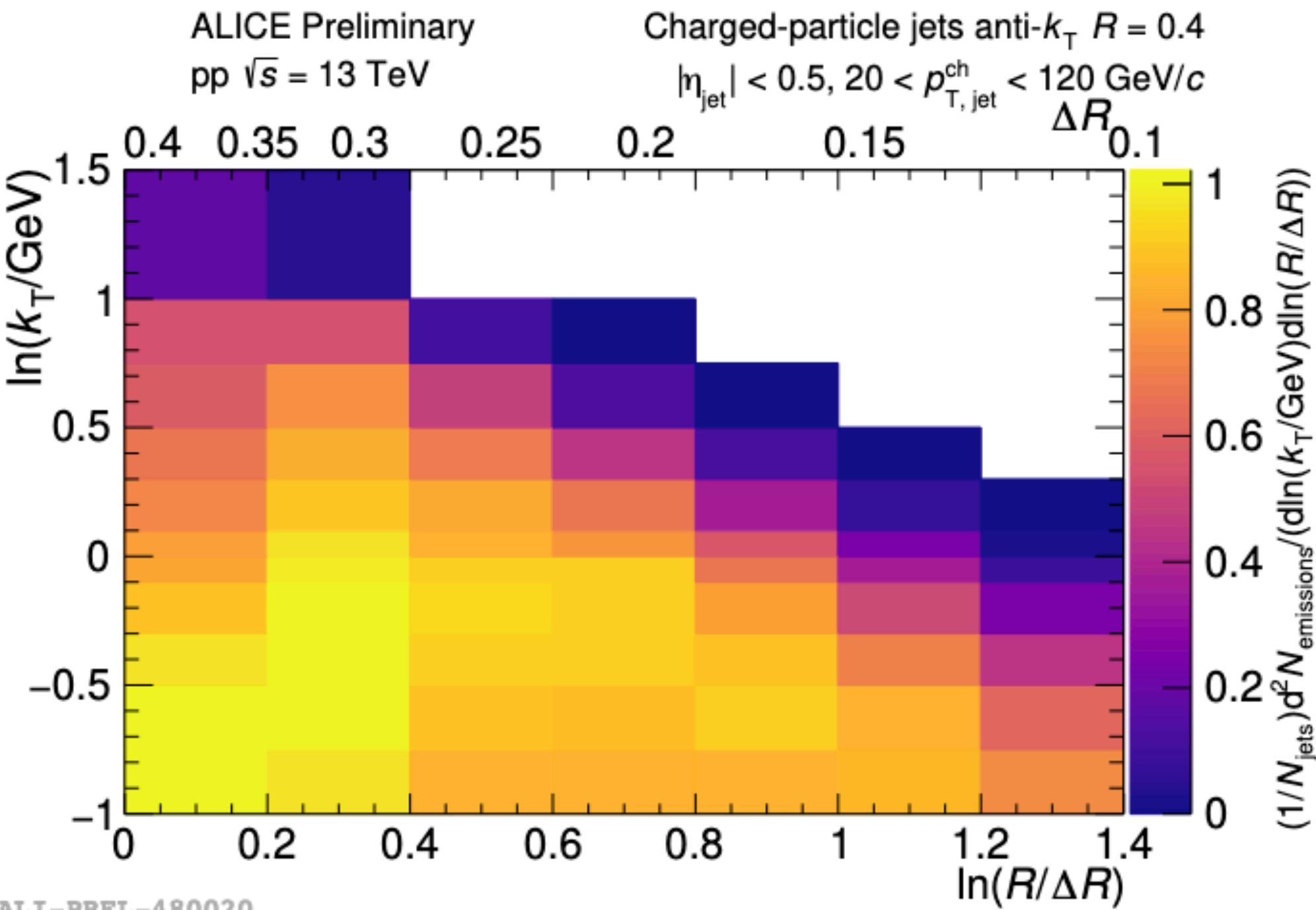
# Lund plane — pp

ALICE-PUBLIC-2021-002



Lund plane density: 
$$\rho(\theta, k_T) = \frac{1}{N_{\text{jets}}} \frac{d^2 n}{d \ln(R/\Delta R) d \ln(k_T)}$$

Dreyer, Salam, Soyez JHEP 12 (2018) 064

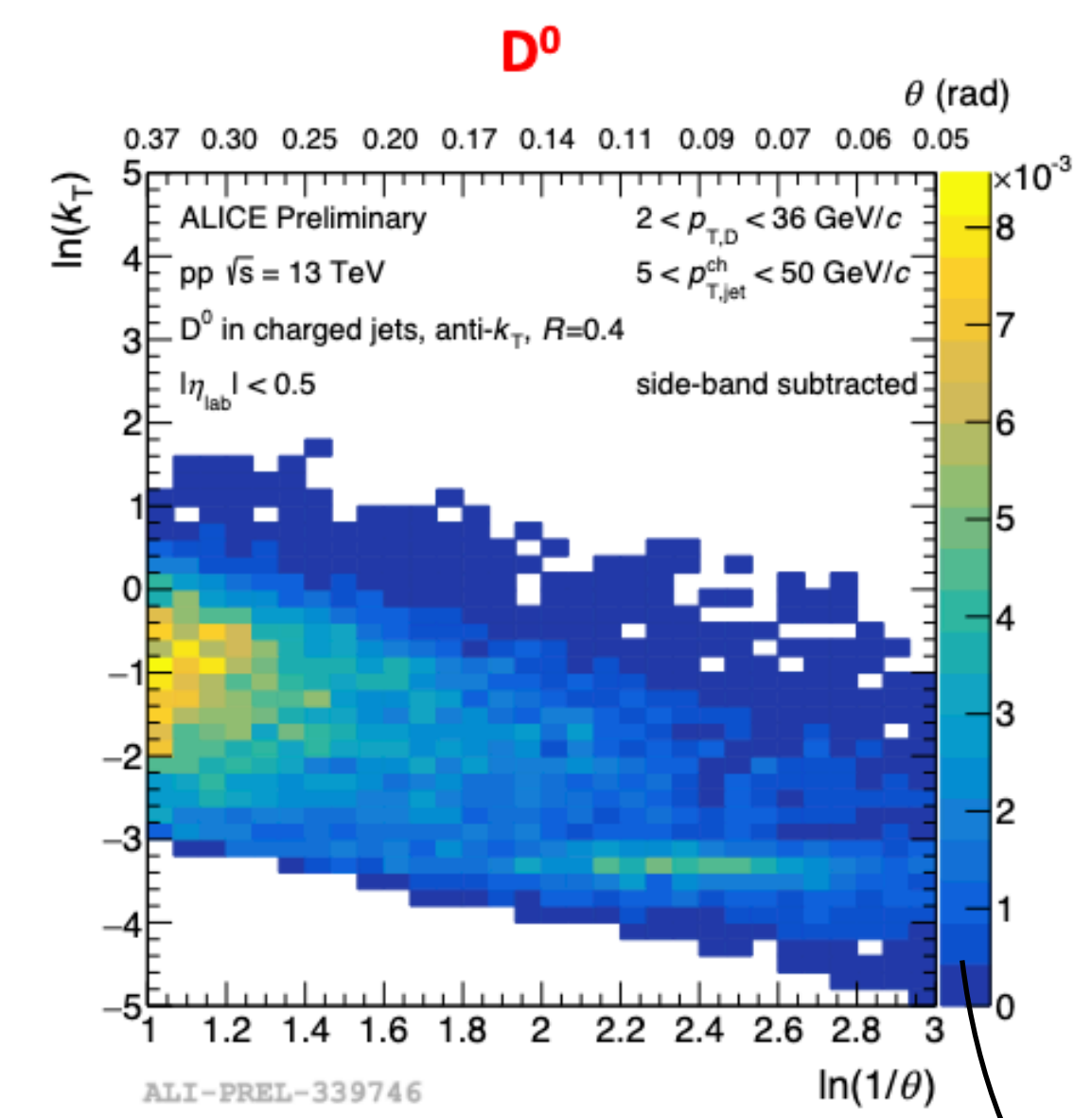


Low- $p_T$  measurement constrains MC generators

See also:  
ATLAS PRL 124 222002 (2020)

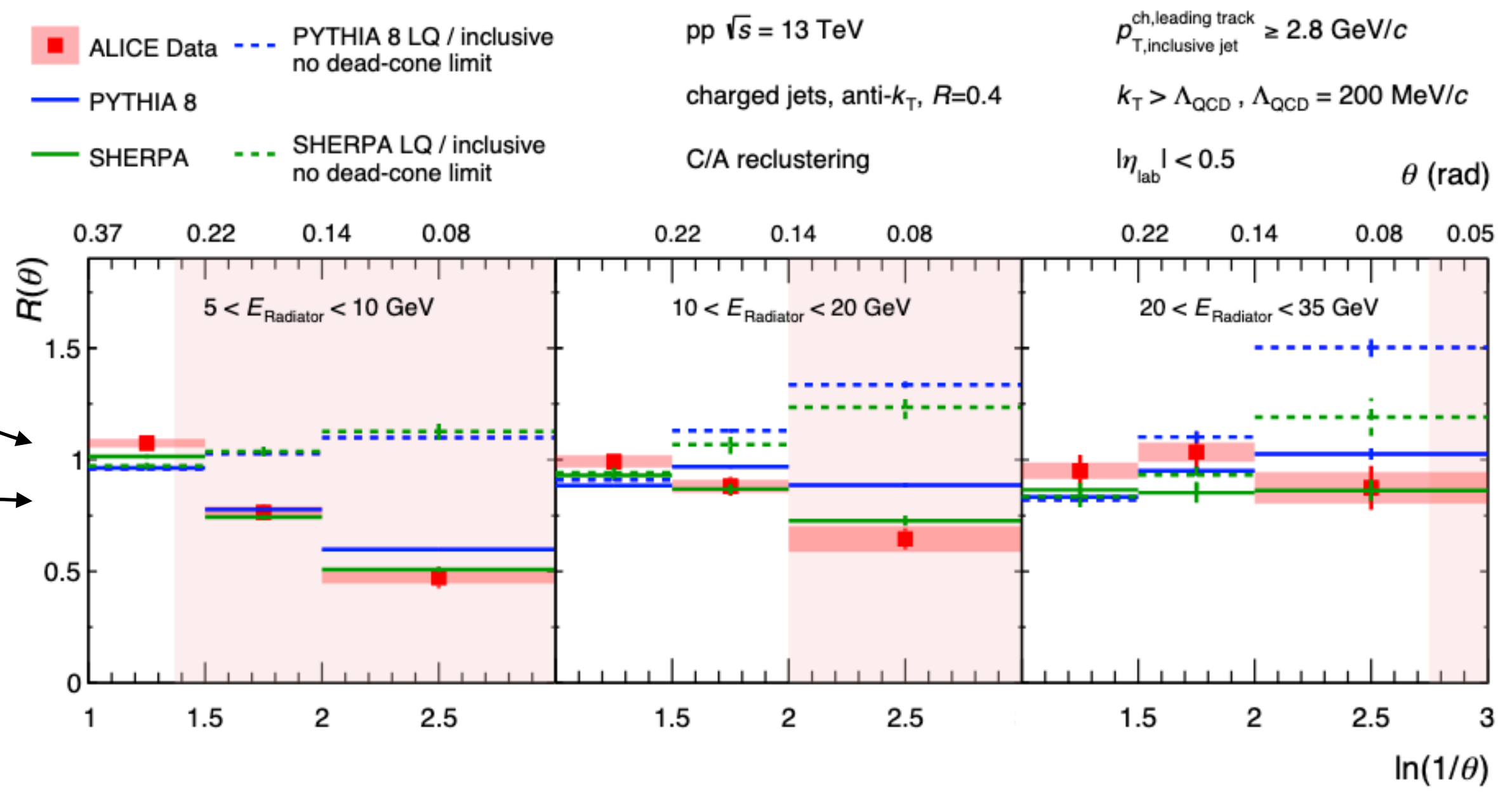
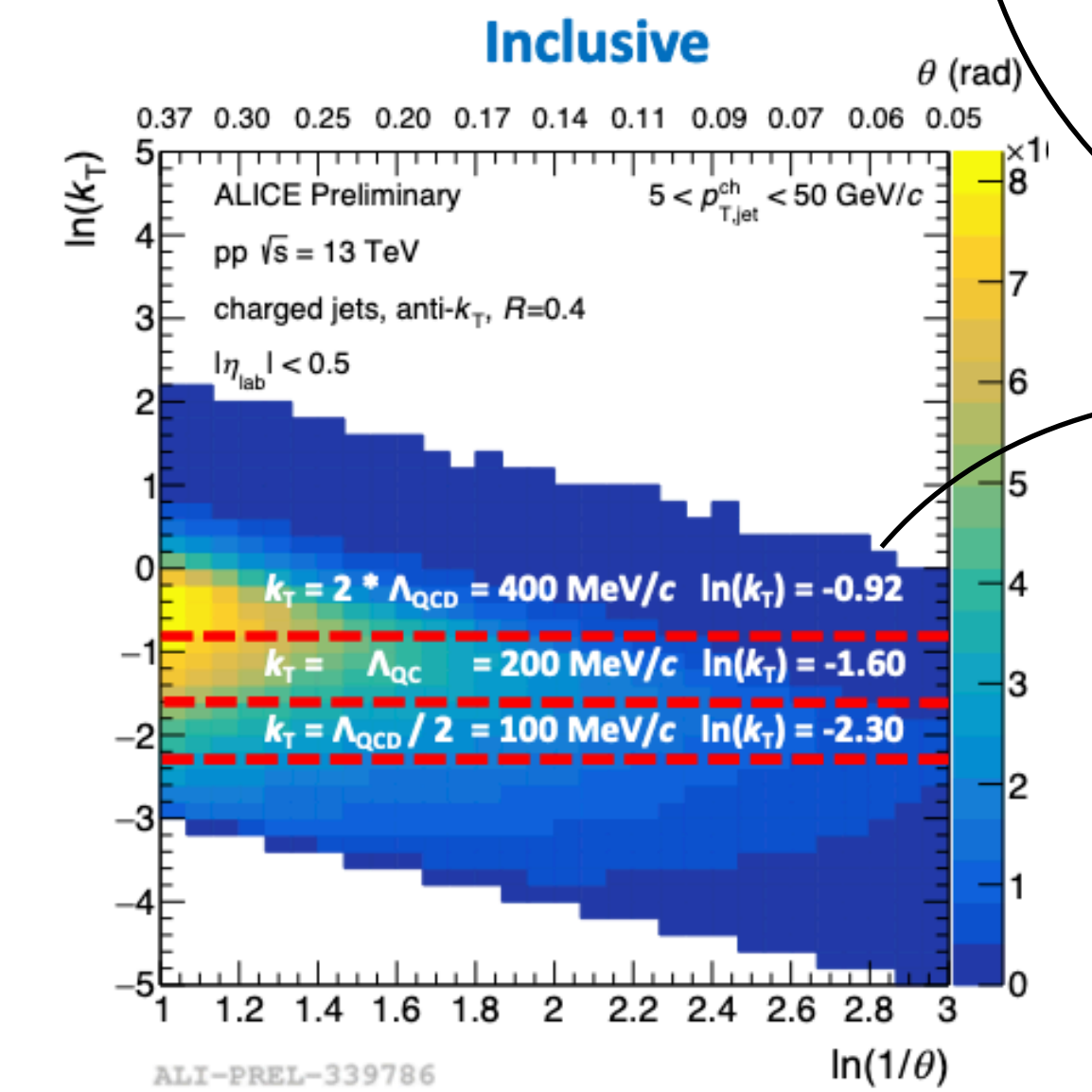
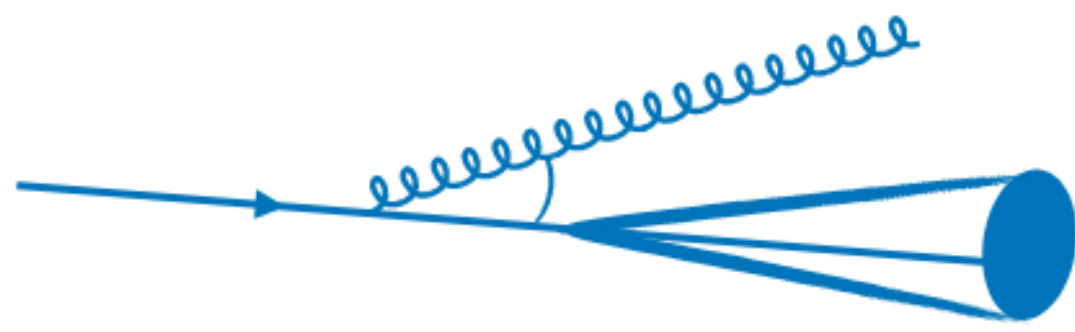
# ALICE Dead Cone

Suppression of radiation emitted by a quark for  $\theta < \frac{m_q}{E_q}$



## Suppression of small-angle splittings in D<sup>0</sup>-tagged jets relative to inclusive jets

$$R(\theta) = \frac{1}{N^{\text{D}^0 \text{ jets}}} \frac{dn^{\text{D}^0 \text{ jets}}}{d\ln(1/\theta)} \bigg/ \frac{1}{N^{\text{inclusive jets}}} \frac{dn^{\text{inclusive jets}}}{d\ln(1/\theta)} \bigg|_{k_T, E_{\text{Radiator}}}$$

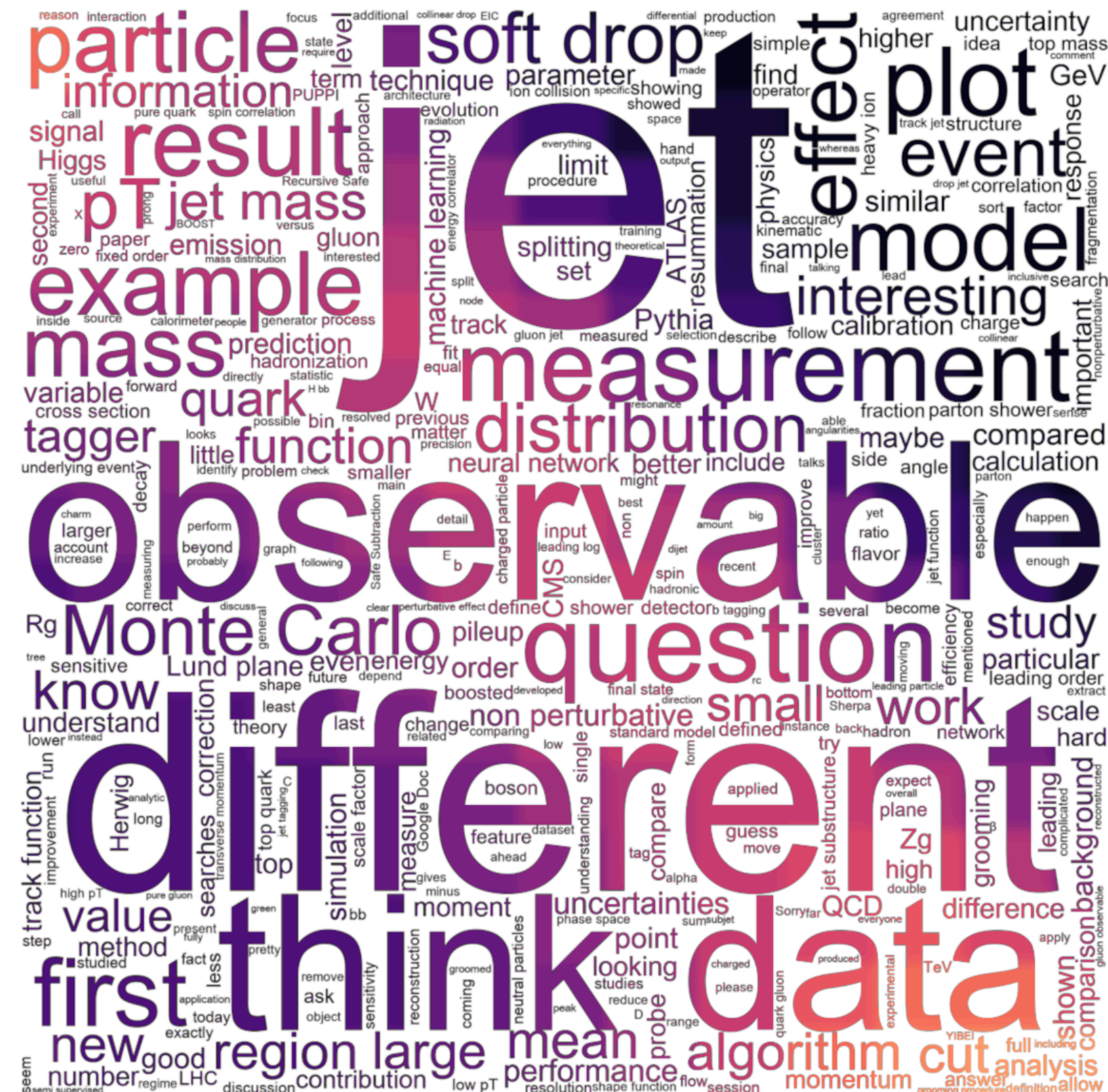


**First direct measurement of the dead cone effect in pp collisions**

□ Suppression decreases as  $E_{\text{radiator}}$  increases:  $\theta < m_q/E_q$

# Concluding remarks

- **BOOST2021 was a successful online meeting full of lively discussion and exchanging ideas.**
- All material is **recorded, captioned and available** on the CDS video server (linked from BOOST2021 indico page).
- **ATLAS and CMS presented very different material** this year — diverging interests?
- ALICE, LHCb and STAR also brought many interesting measurements: **BOOST is growing**, and will get even bigger with the EIC!
- Theory community seems self-reflective: **searching for the right places to push** for the next breakthrough.
  - I'm very **excited** to think about the new ideas which will result from this process!



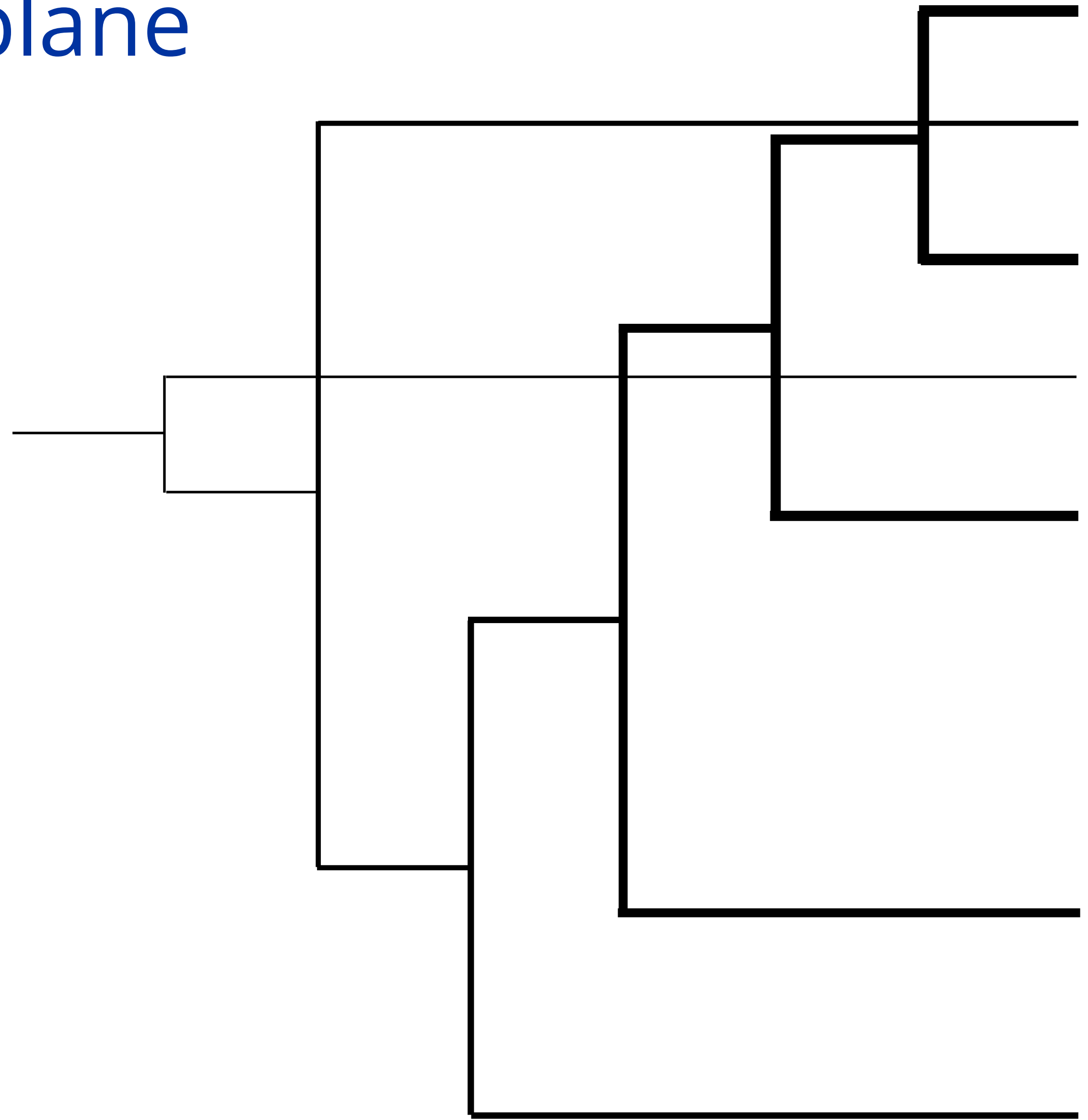
*A visual summary of the BOOST2021 discussions, generated from the plenary talk, Q&A session and panel discussion captions!*

Soft-drop and the Lund jet plane

# Soft-drop & the Lund jet plane

1. **Begin with an anti- $k_t$  jet.**
2. Recluster jet constituents using **Cambridge/Aachen (C/A)** algorithm (angular-ordering).
3. **Iterating inward from widest-angle radiation**, discard subjects when they fail the Soft Drop condition.
  - Two parameters:  $z_{\text{cut}}$  and  $\beta$ .
4. When the SD condition is satisfied, **stop!**
  - **Soft** and **Wide-Angle** radiation is removed.

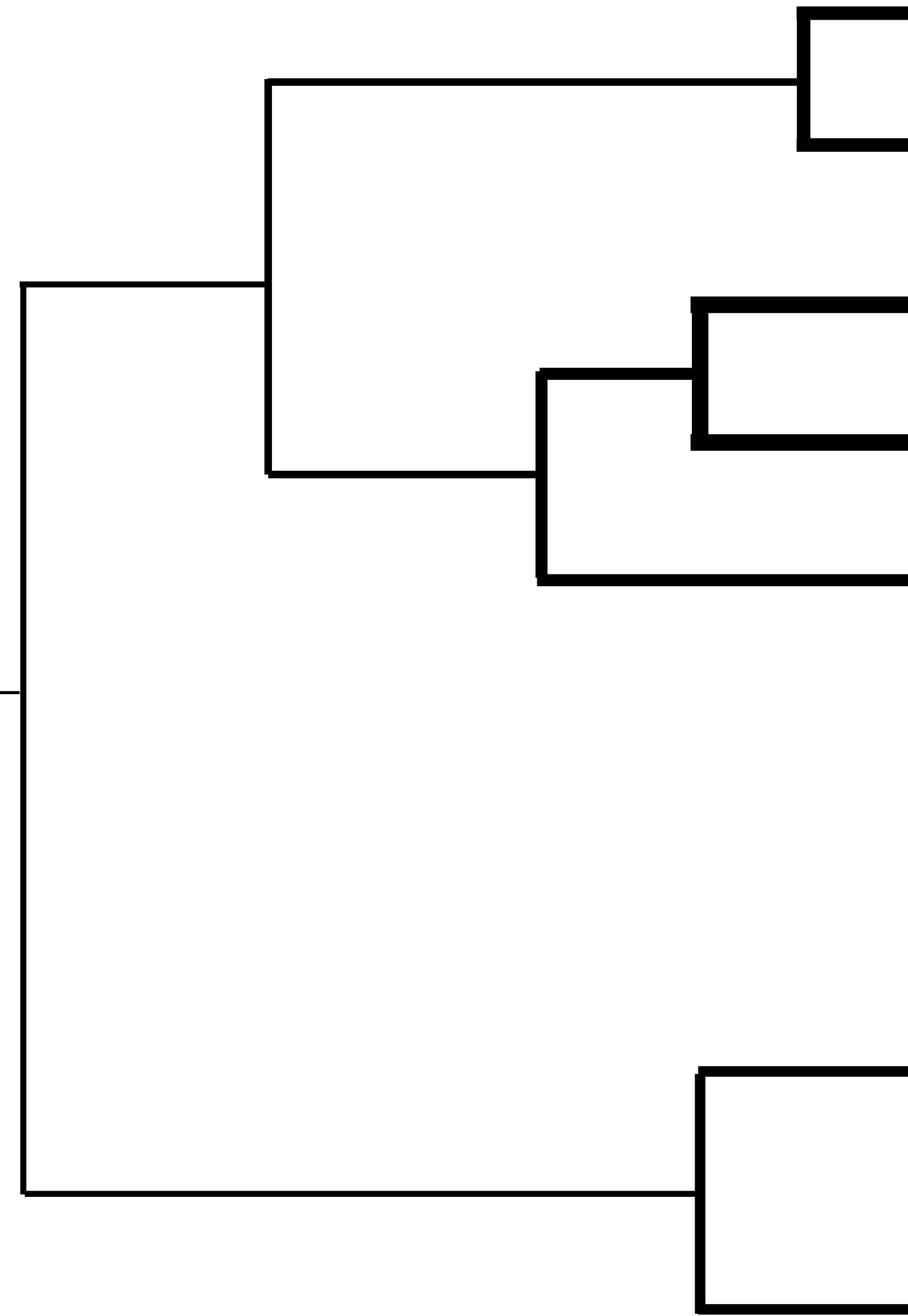
$j$



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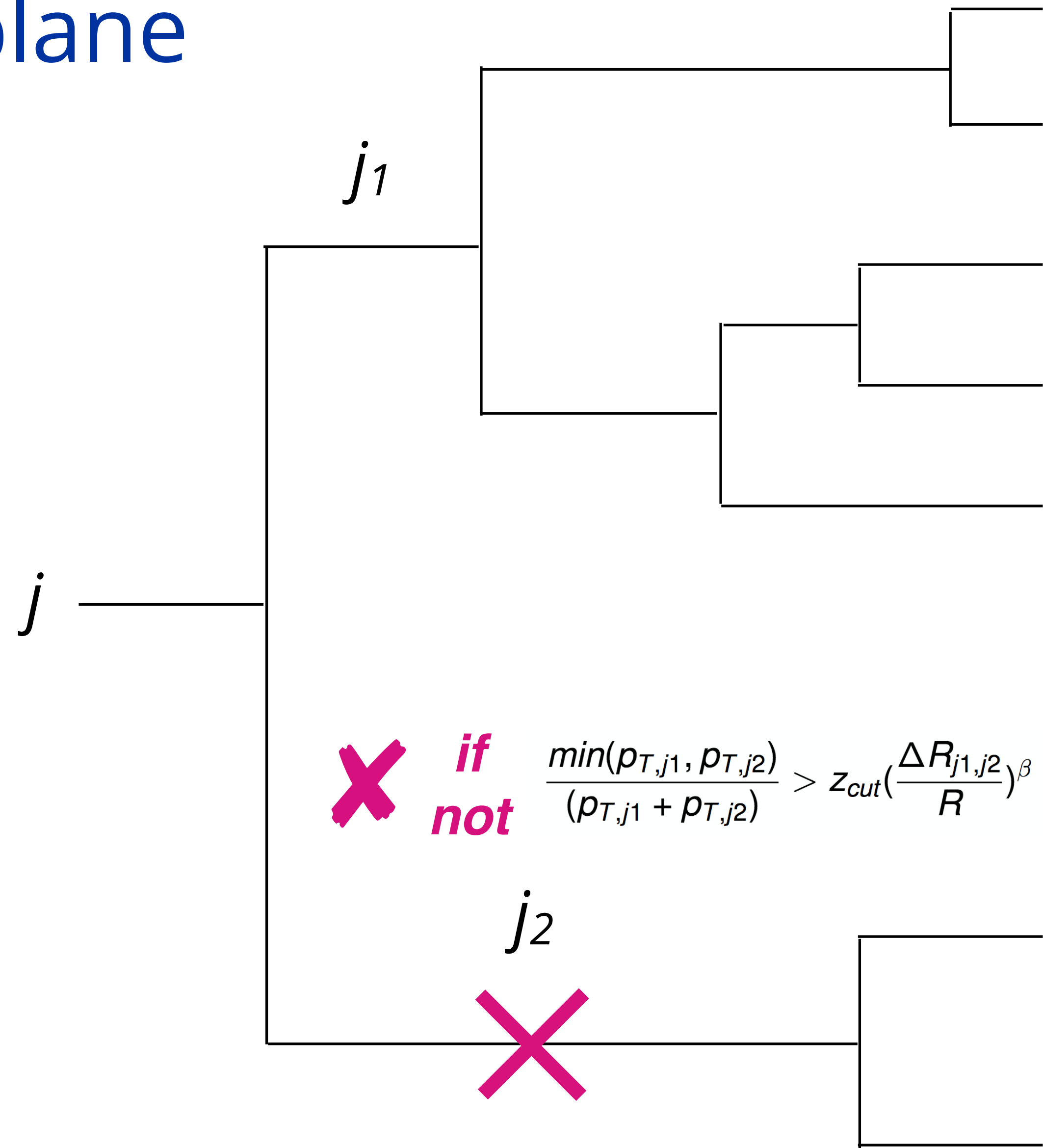
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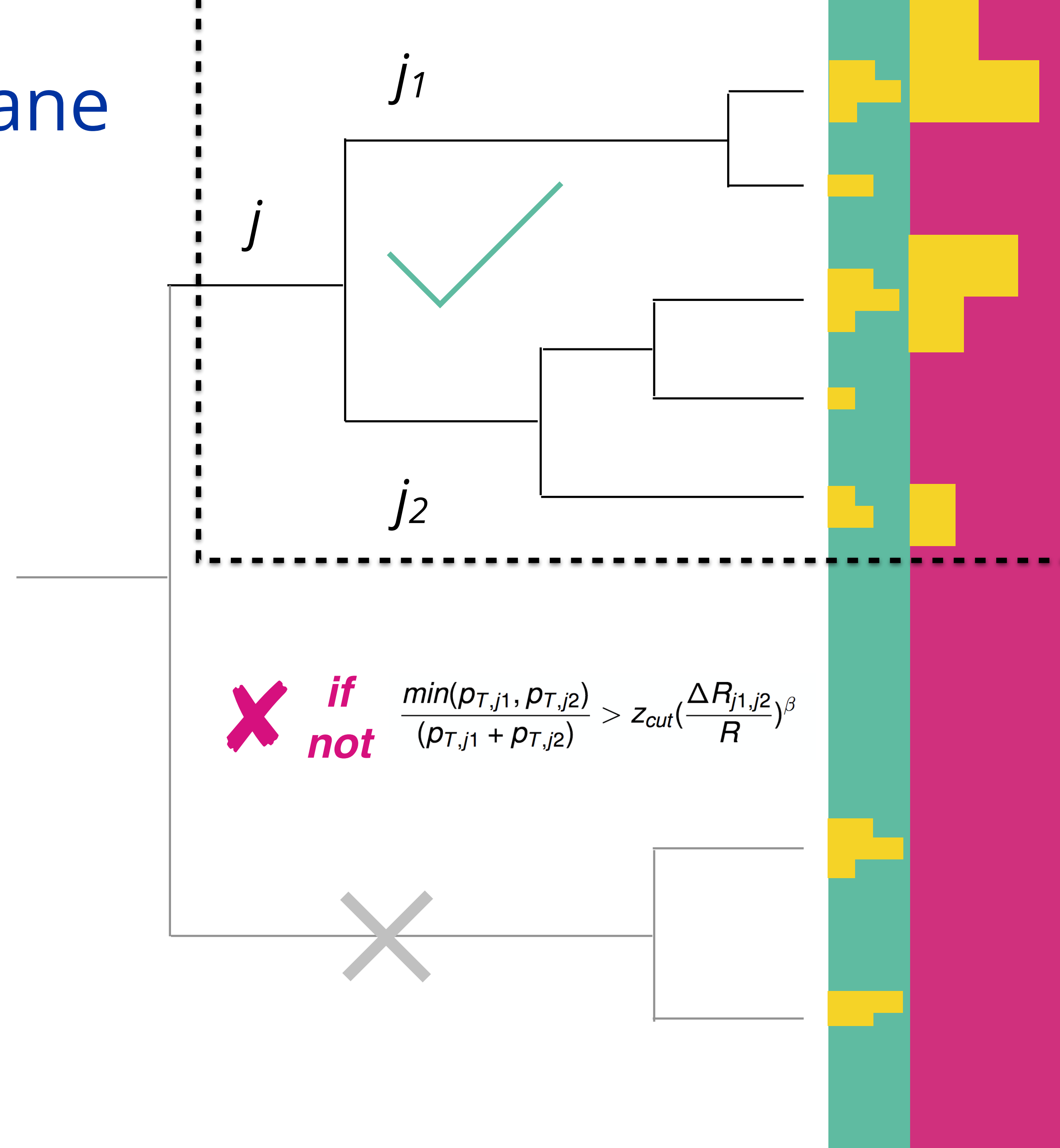
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# Lund jet plane

QCD radiation within jets  
is approx. uniform in  
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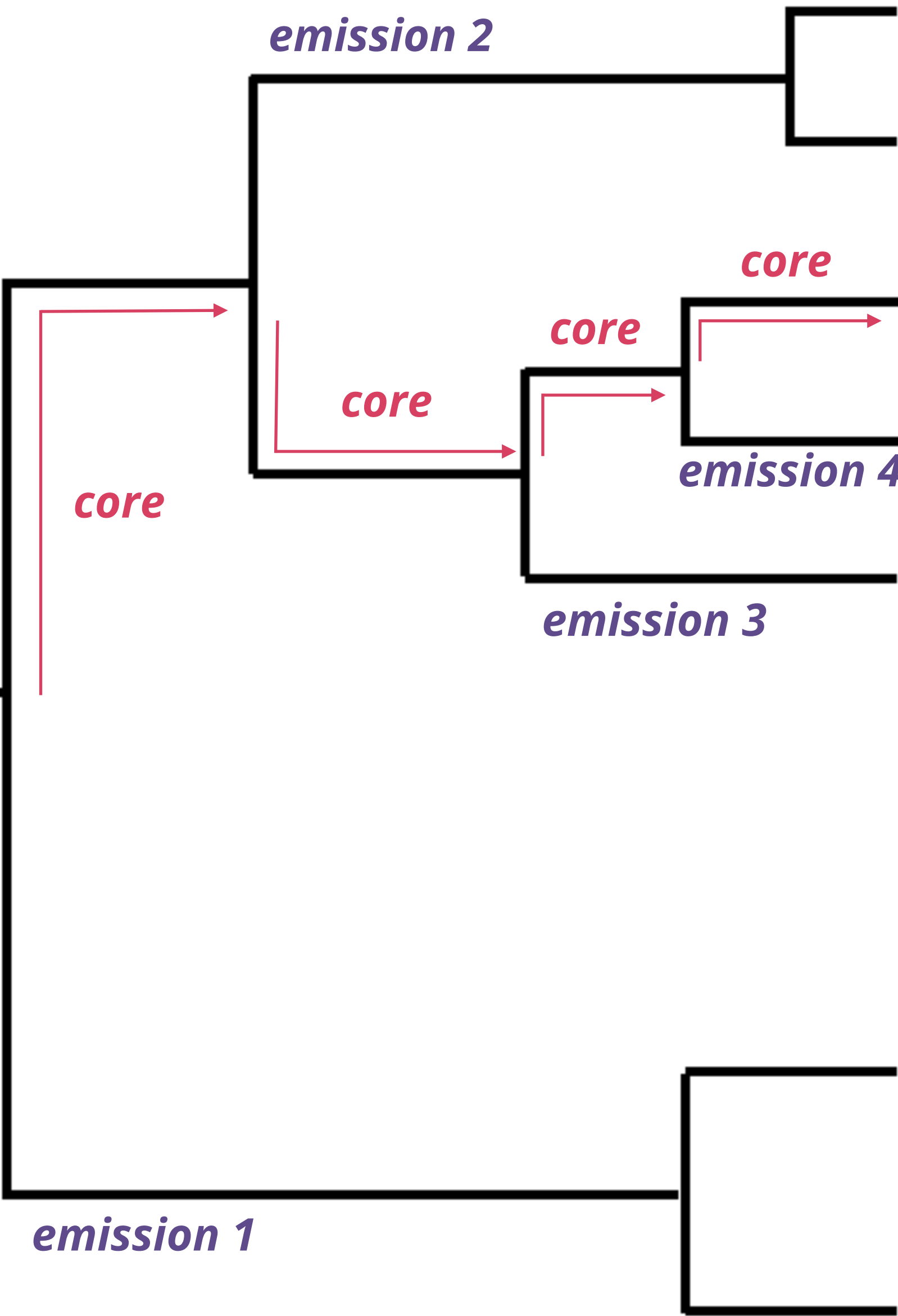
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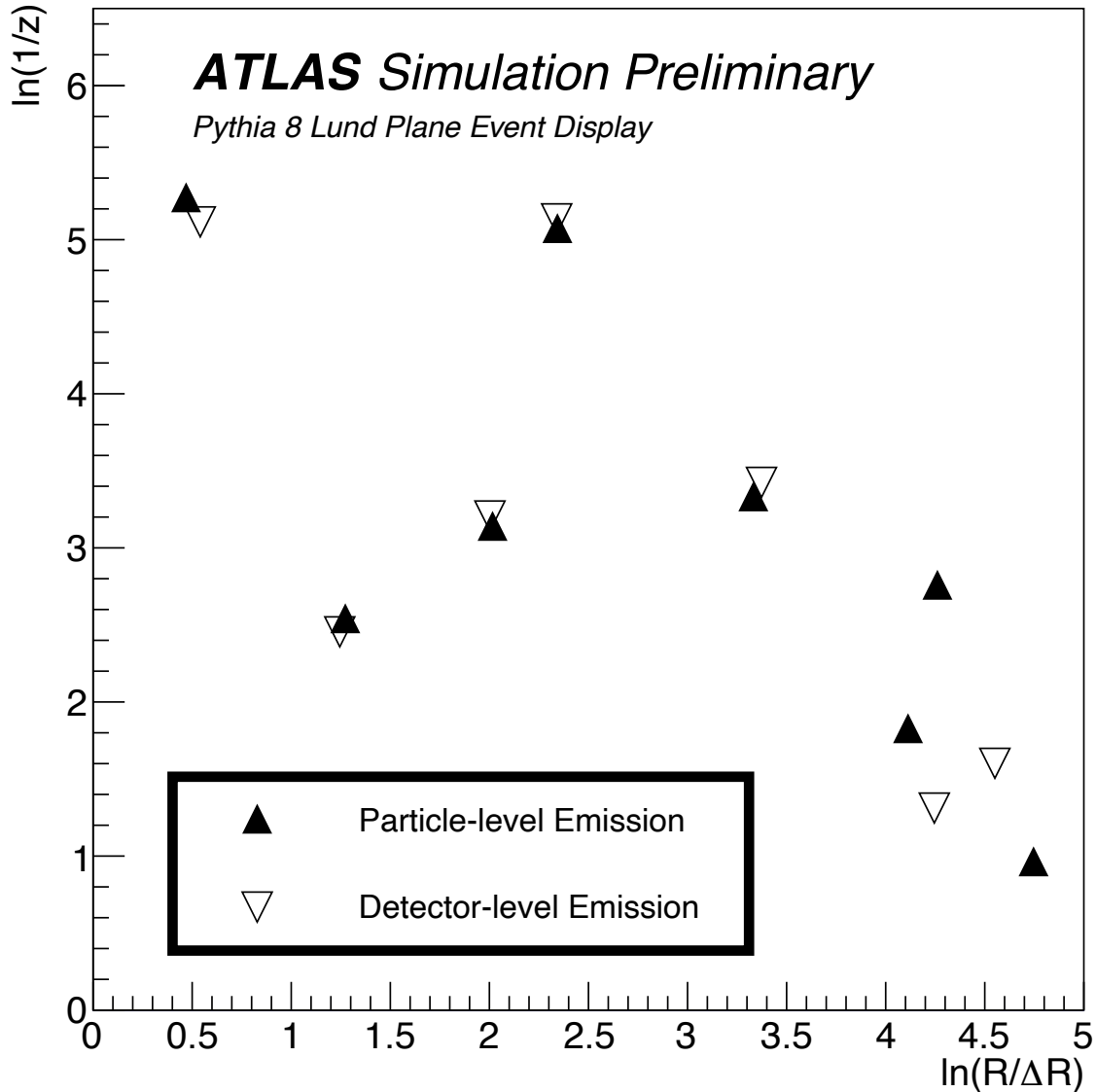
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